US005694187A

United States Patent [19]

Abileah et al.

[11] Patent Number: 5,694,187

[45] Date of Patent: *Dec. 2, 1997

[54] **LCD INCLUDING A NEGATIVE BIAXIAL RETARDER ON EACH SIDE OF THE LIQUID CRYSTAL LAYER**

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[73] Assignee: **OIS Optical Imaging Systems, Inc.**, Northville, Mich.

[*] Notice: The term of this patent shall not extend beyond the expiration date of Pat. No. 5,570,214.

[21] Appl. No.: **785,900**

[22] Filed: **Jan. 21, 1997**

Related U.S. Application Data

[63] Continuation of Ser. No. 711,797, Sep. 10, 1996, which is a continuation of Ser. No. 167,652, Dec. 15, 1993, Pat. No. 5,570,214.

[51] Int. Cl.^{6} G02F 1/1335

[52] U.S. Cl. 349/120; 349/118

[58] Field of Search 349/118, 120, 349/119

[56] **References Cited**

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5,550,662	8/1996	Bos	349/117
5,570,214	10/1996	Abileah et al.	349/117

Primary Examiner—Anita Pellman Gross
Attorney, Agent, or Firm—Myers Liniak & Berenato

[57] **ABSTRACT**

A normally white twisted birefringent liquid crystal display having first and second retardation films having retardation values of about 80–200 nm on opposite sides of a liquid crystal layer for the purpose of expanding the viewing angles of the display. Also, the viewing zone of this normally white display can be shifted vertically by rotating the optical axes of the retardation films so as to position the viewing zone away from an inversion area.

5 Claims, 46 Drawing Sheets

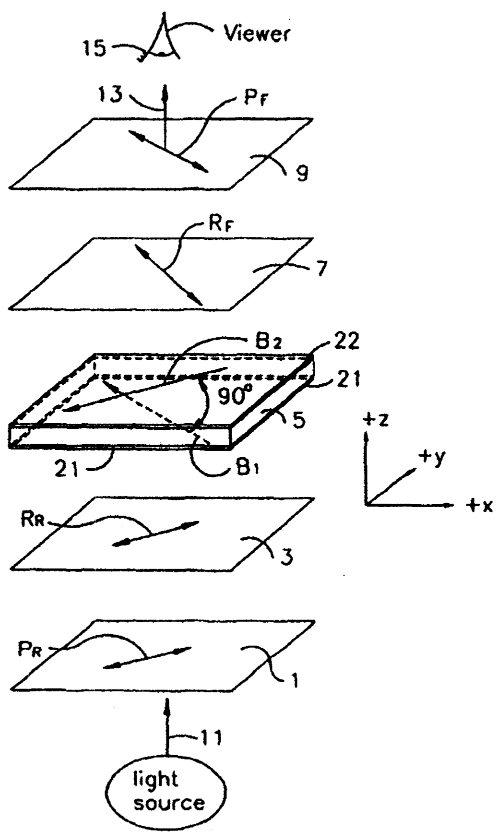


FIG. 1 (Prior Art)

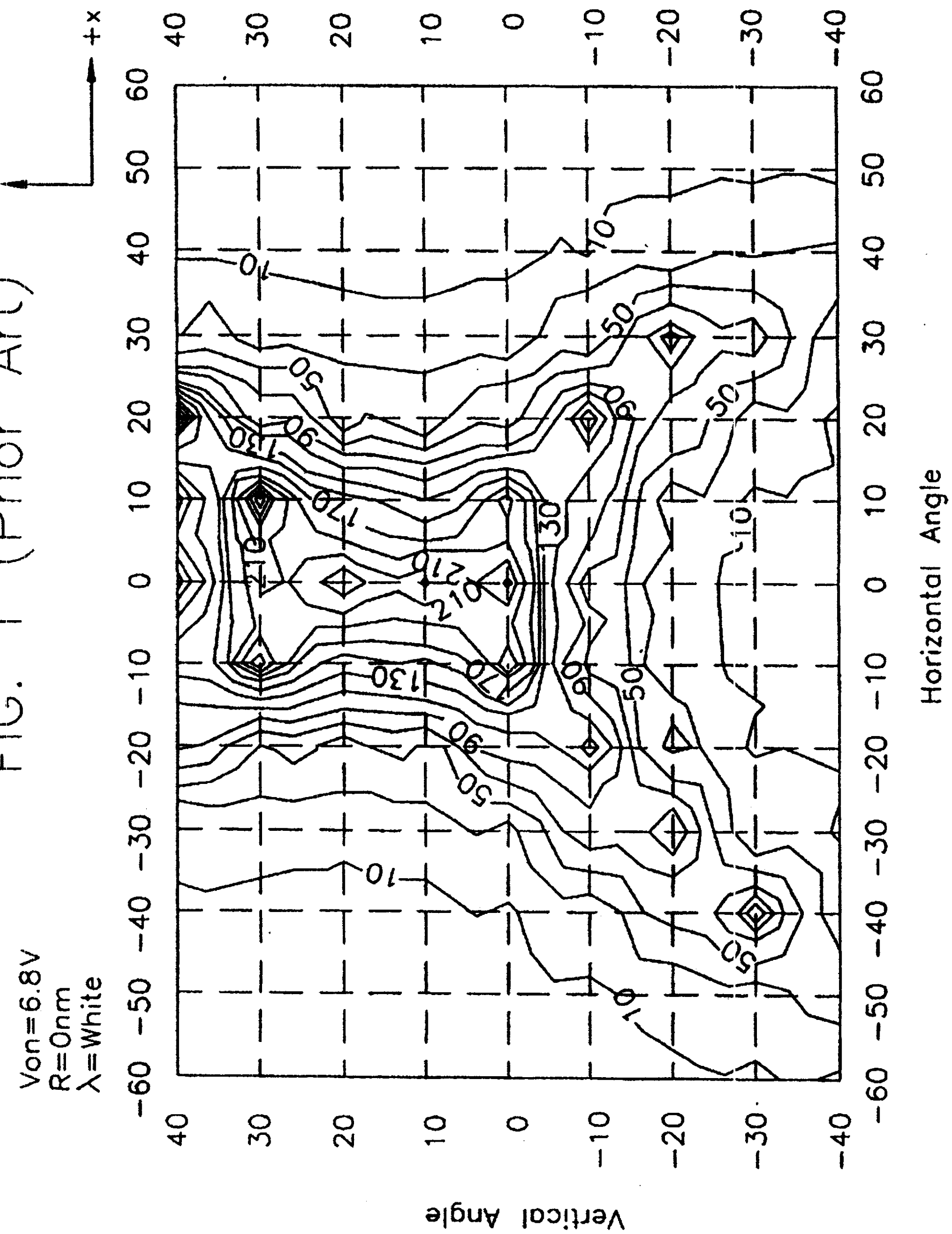


FIG. 2 (Prior Art)

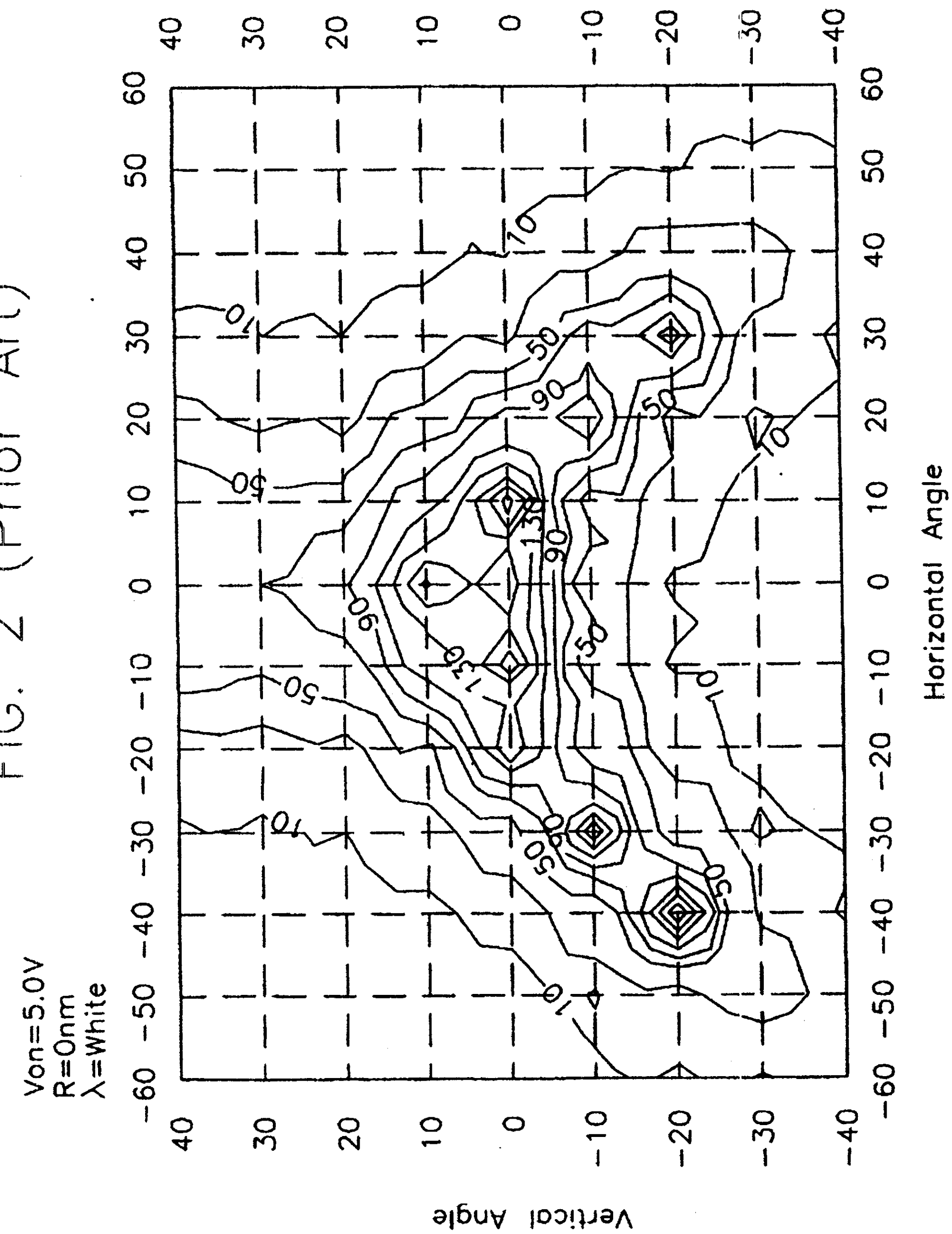


FIG. 3 (Prior Art)

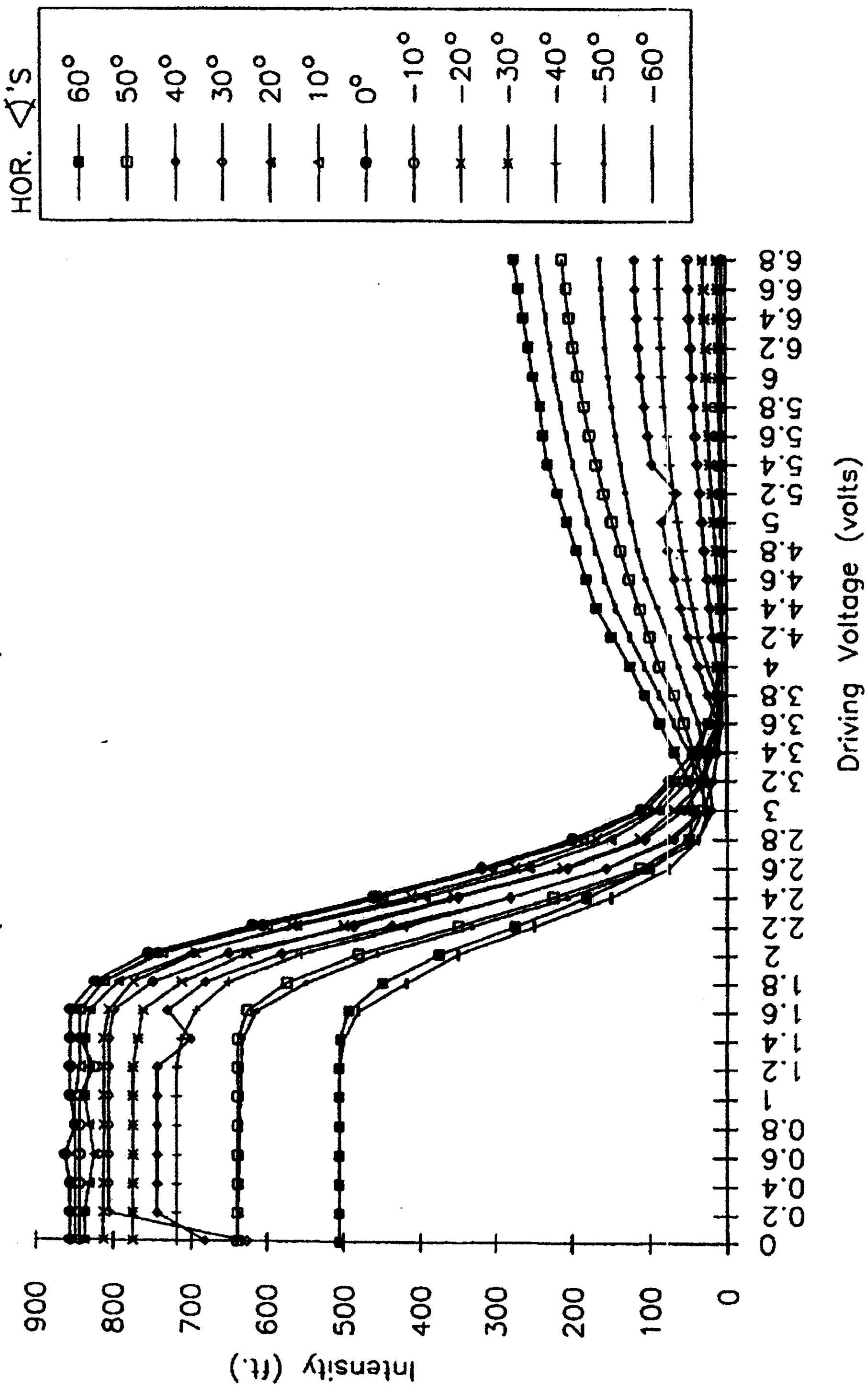
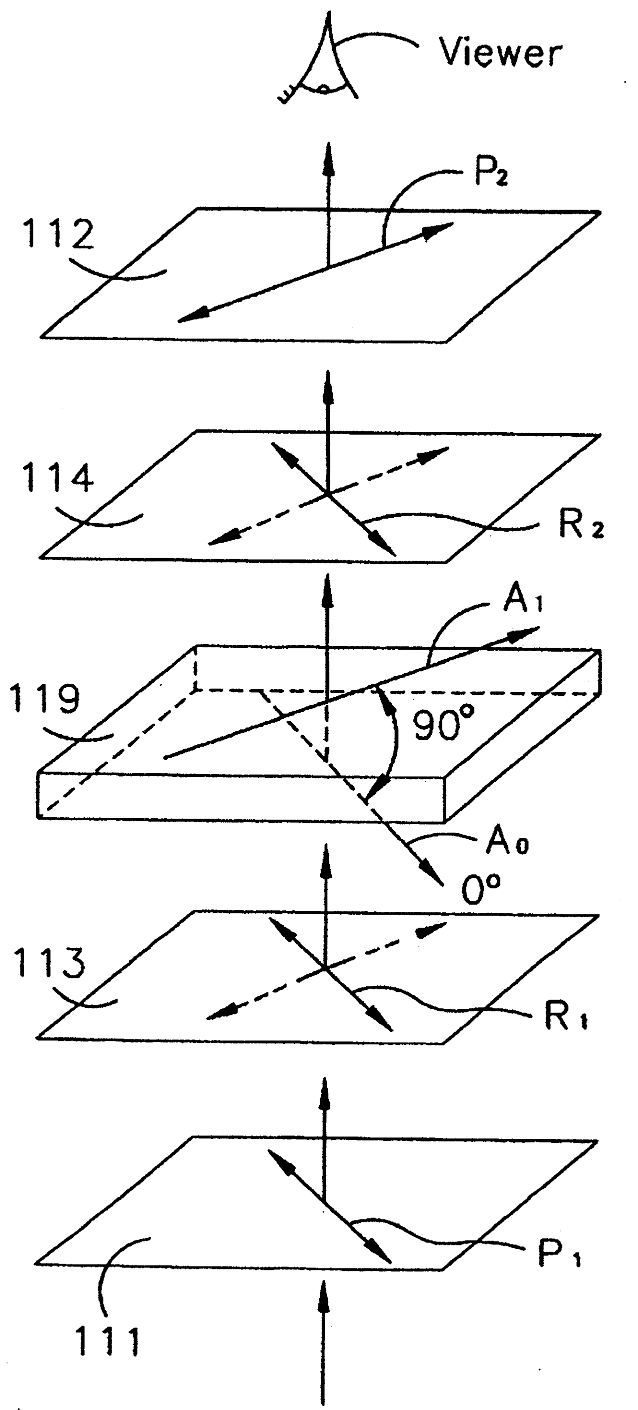


Fig. 4 (Prior Art)



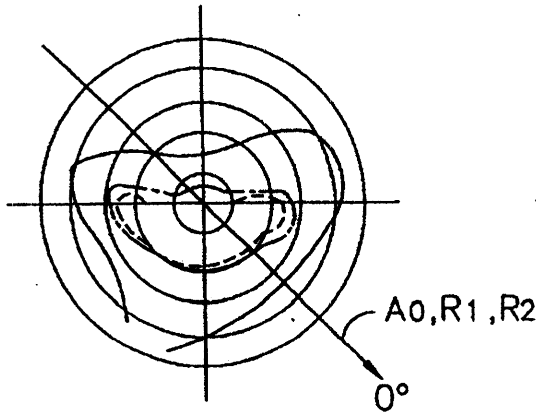


Fig. 5A (Prior Art)

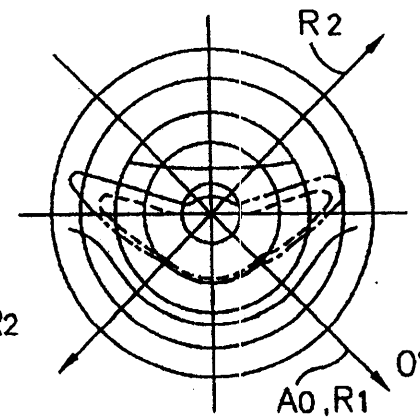


Fig. 5B (Prior Art)

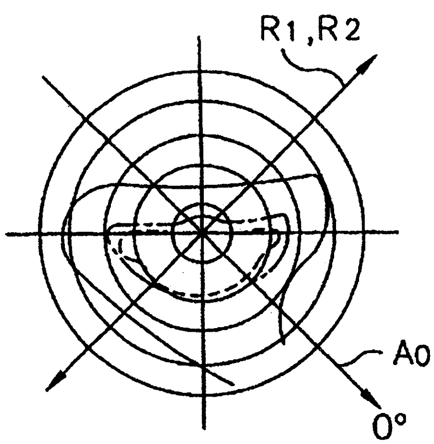


Fig. 5C (Prior Art)

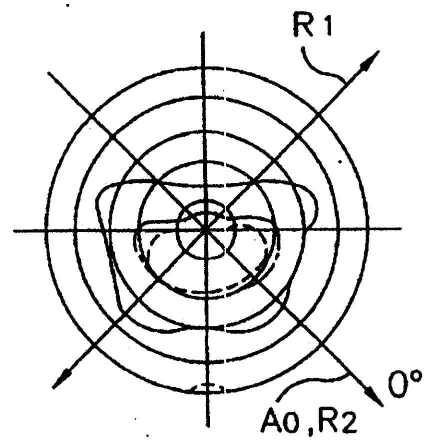
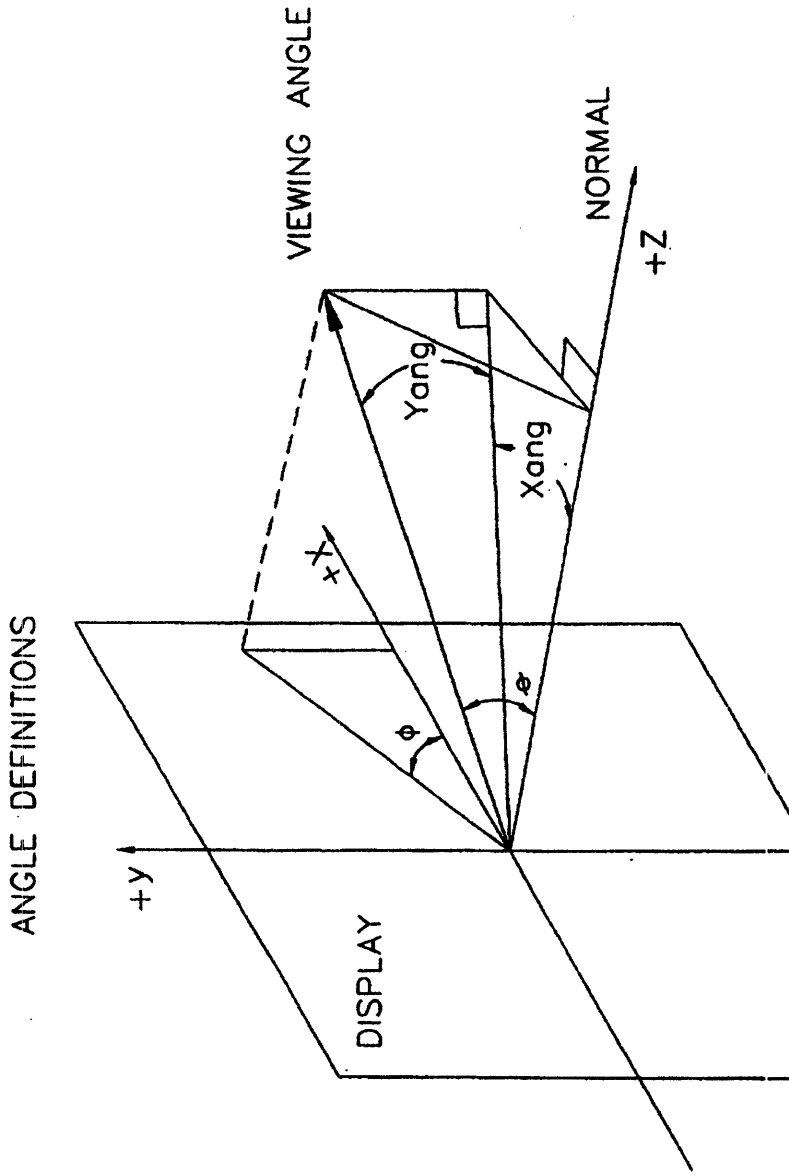


Fig. 5D (Prior Art)

- - - - - - - -	100:1
– – —— – –	50:1
————	10:1



Yang – Vertical angle
Xang – Horizontal angle

Fig. 6

FIG. 7

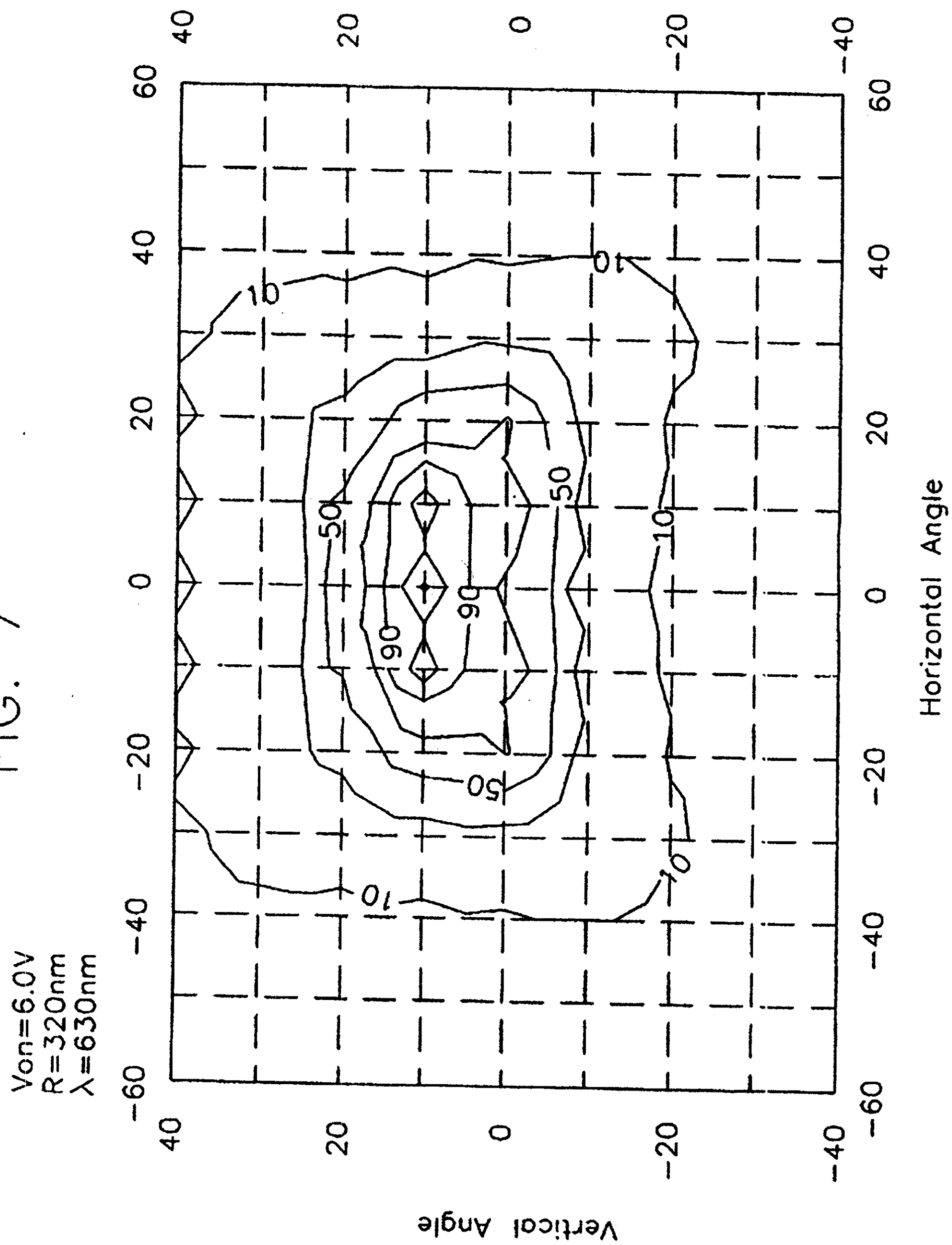

Von=6.0V
R=320nm
λ=630nm
Horizontal Angle
Vertical Angle
10
50
90

FIG. 8

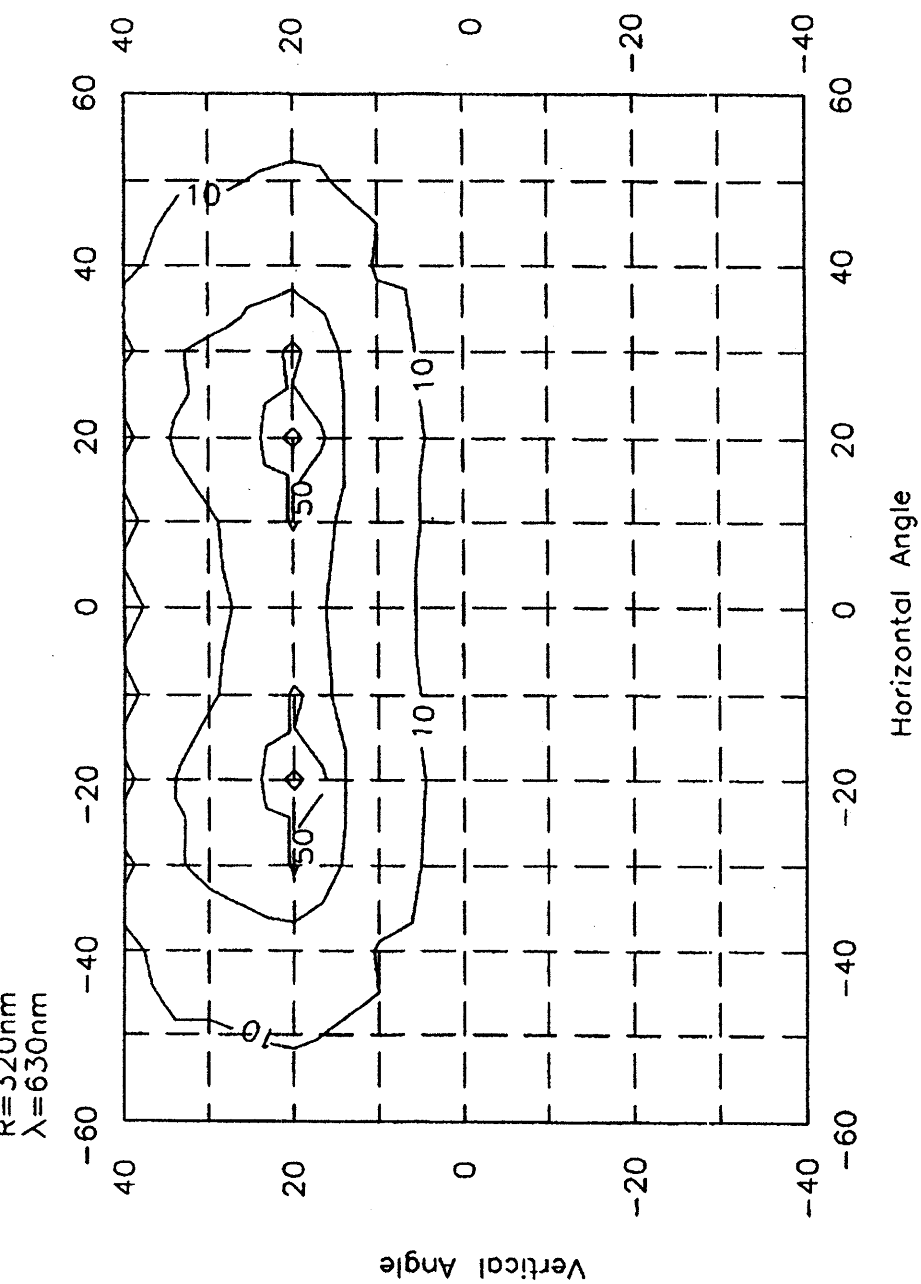
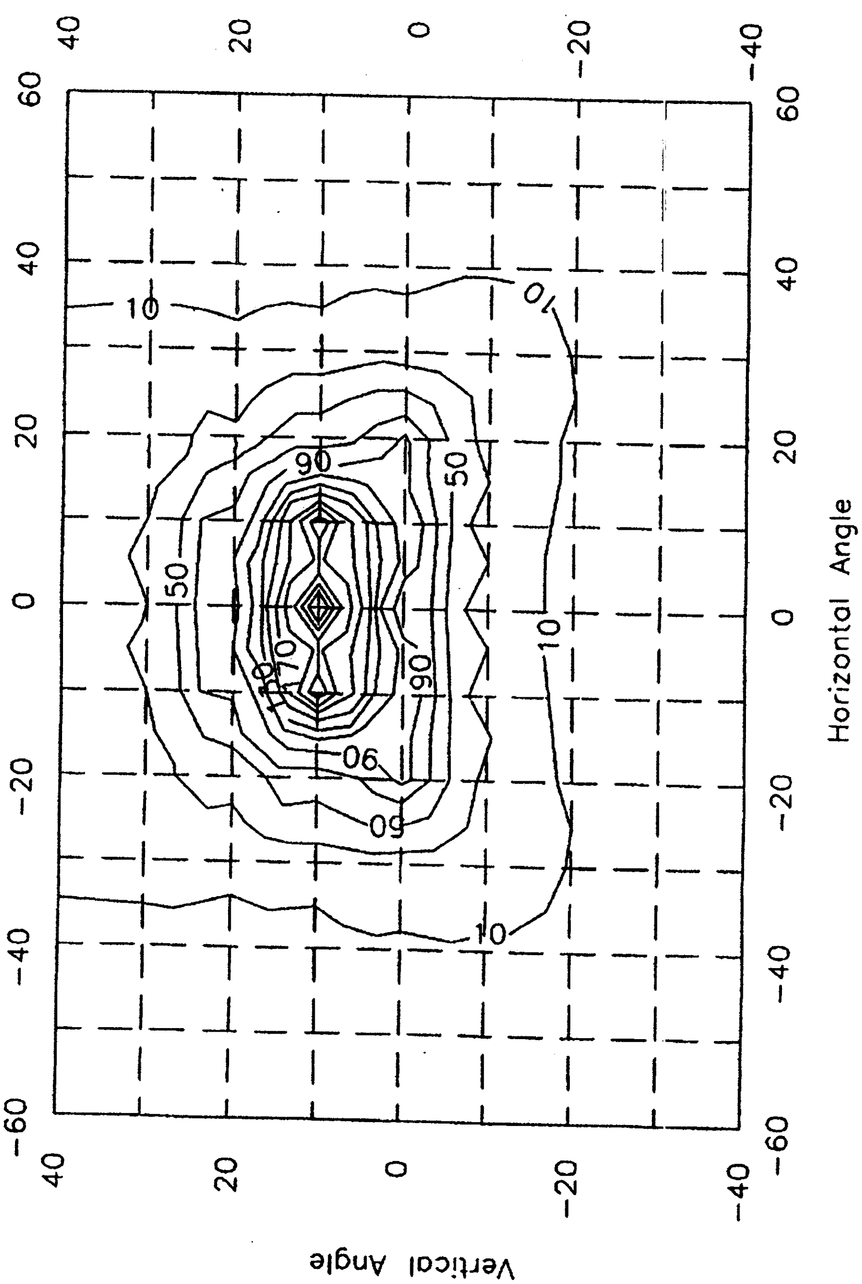

Von=5.0V
R=320nm
λ=630nm
Horizontal Angle
Vertical Angle
10
50

FIG. 9



Von=6.8V
R=320nm
λ=550nm

FIG. 10

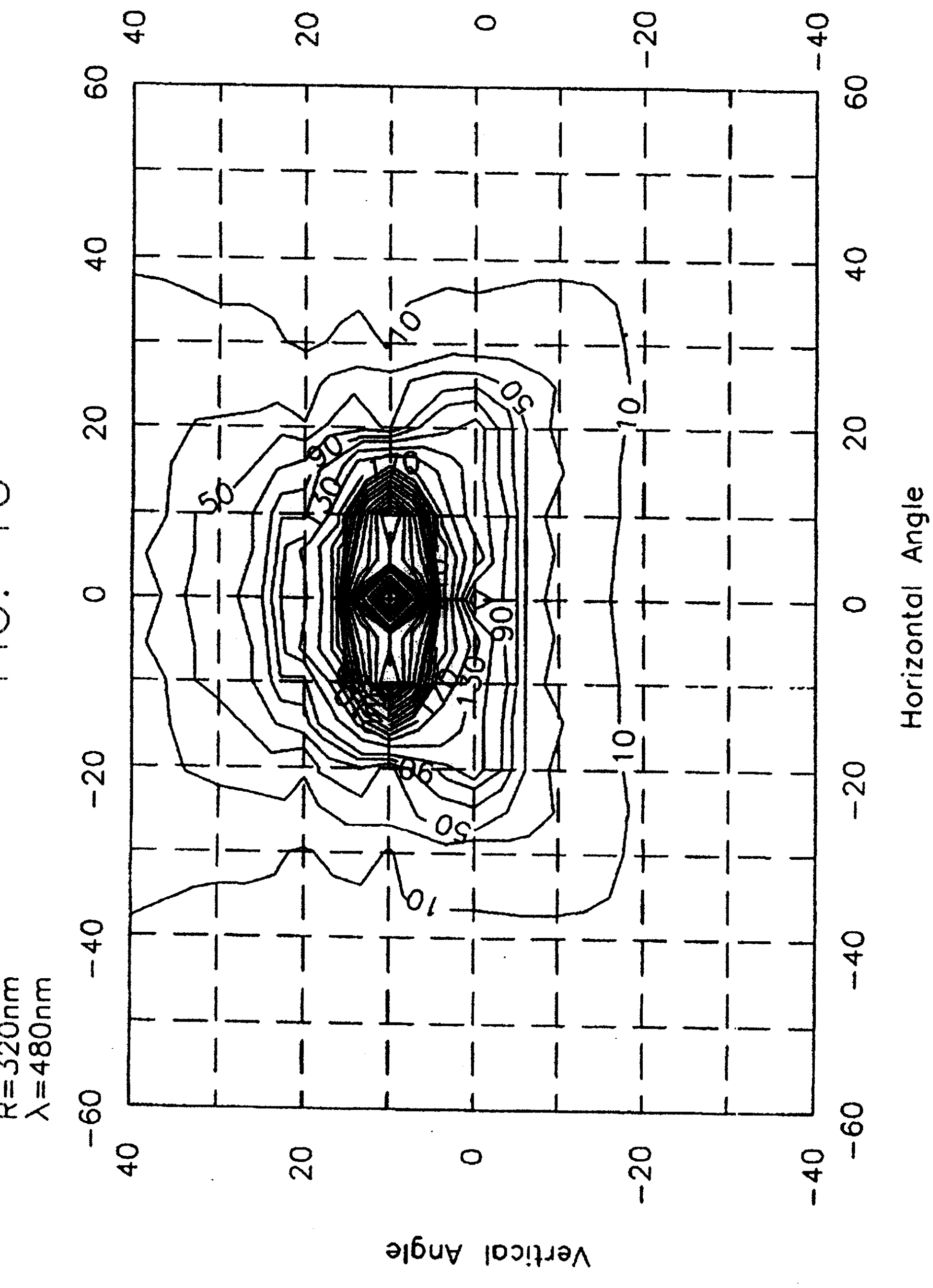
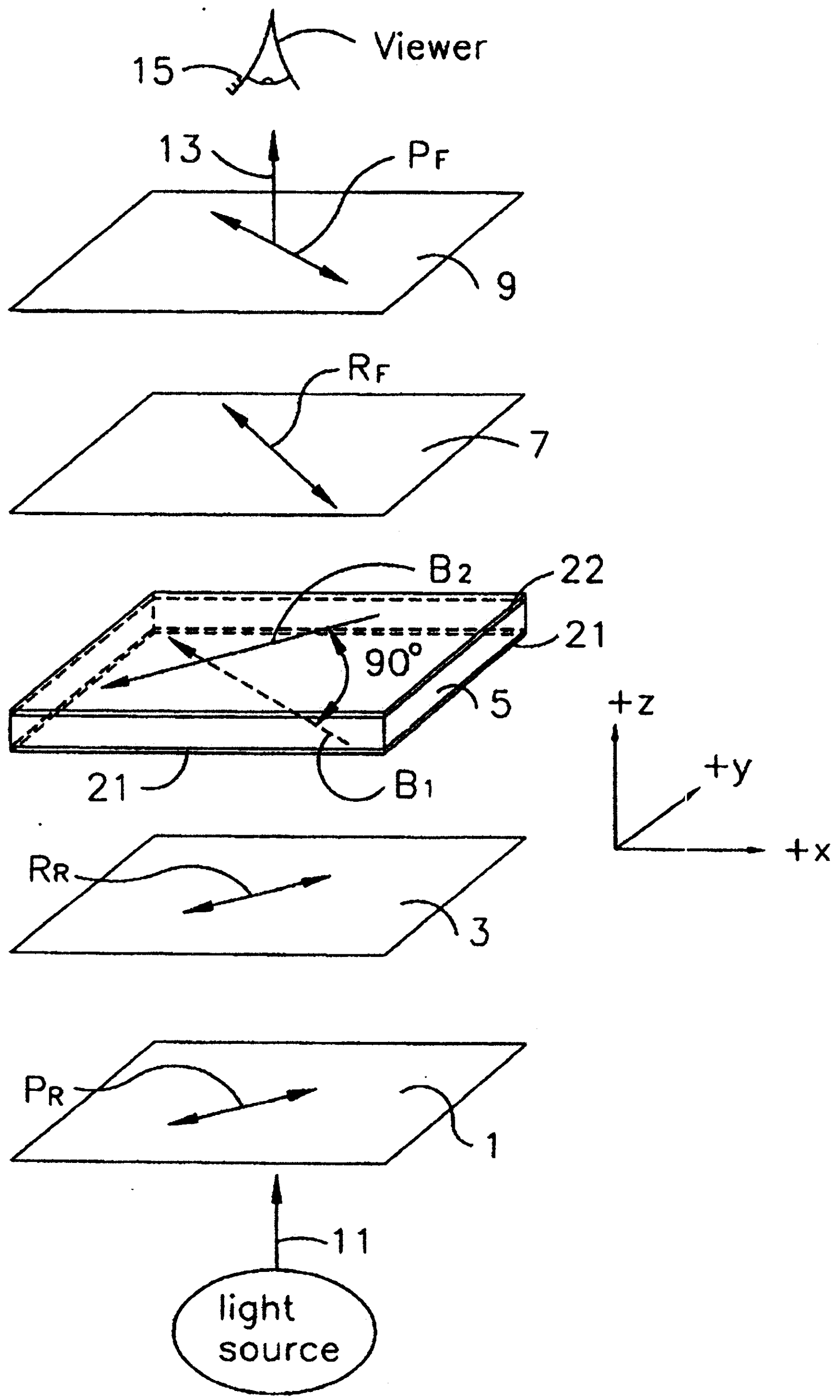

Von=6.8V
R=320nm
λ=480nm
Horizontal Angle
Vertical Angle
10
50
90
130
170

Fig. 11(a)



Viewer
15
13
PF
9
RF
7
B2
22
21
90°
5
21
B1
+z
+y
+x
RR
3
PR
1
11
light source

Fig. 11(b)

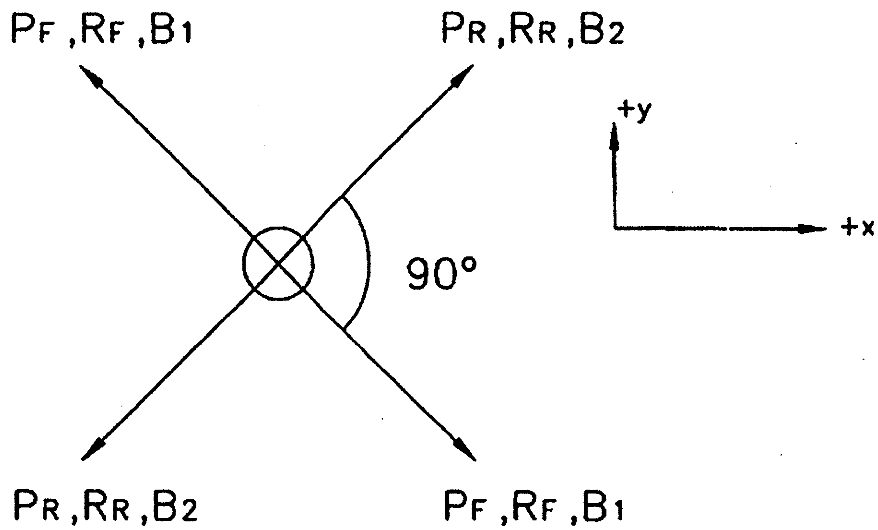


Fig. 11(c)

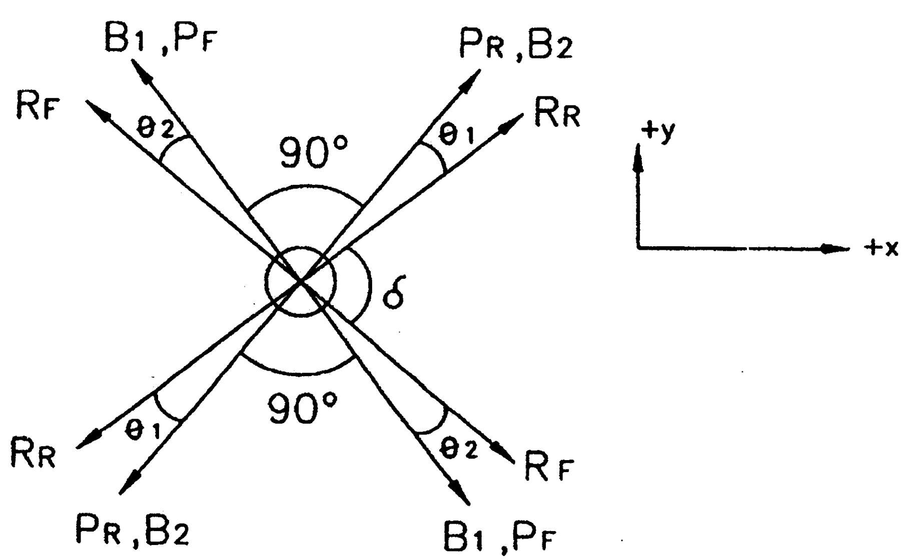
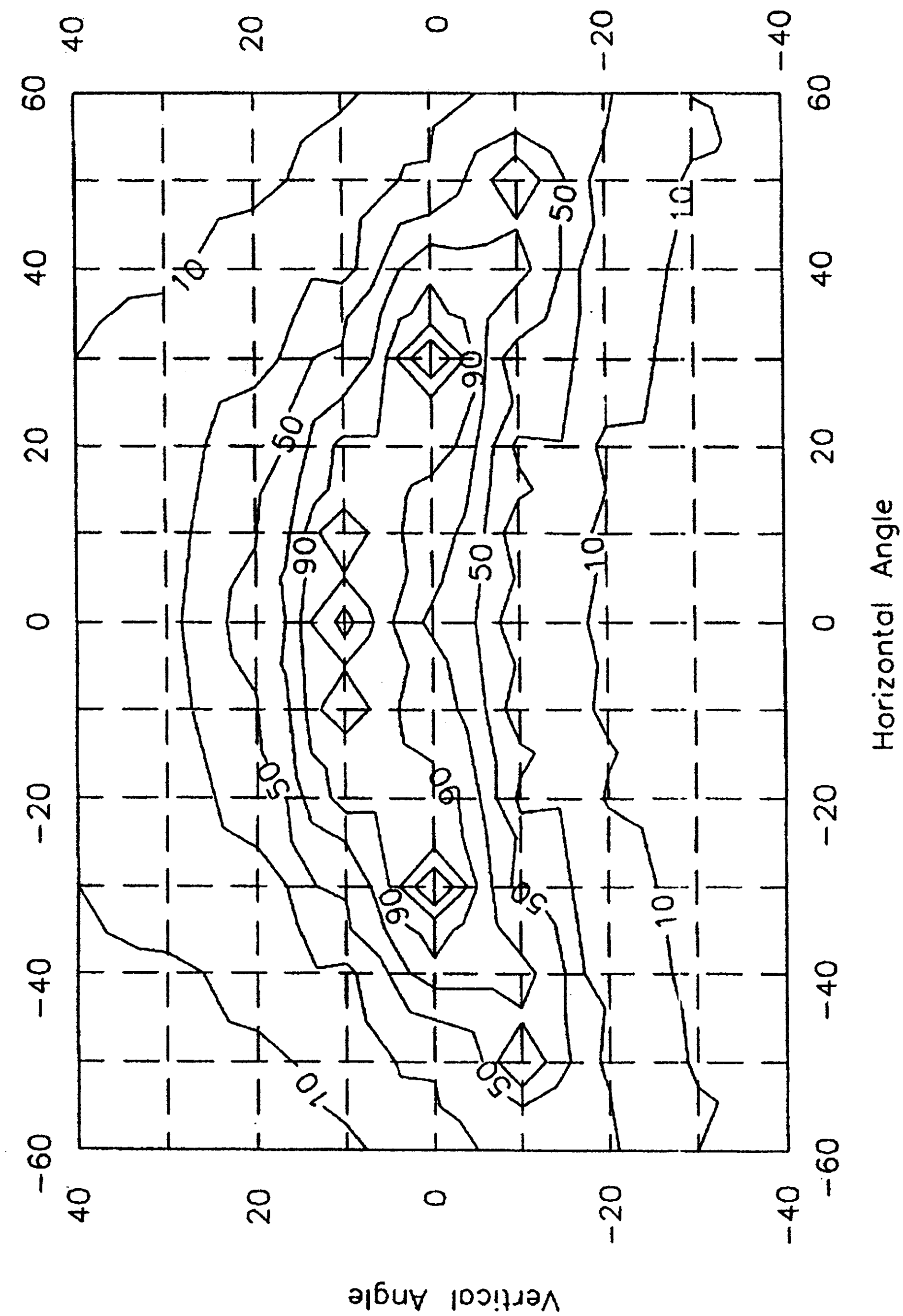
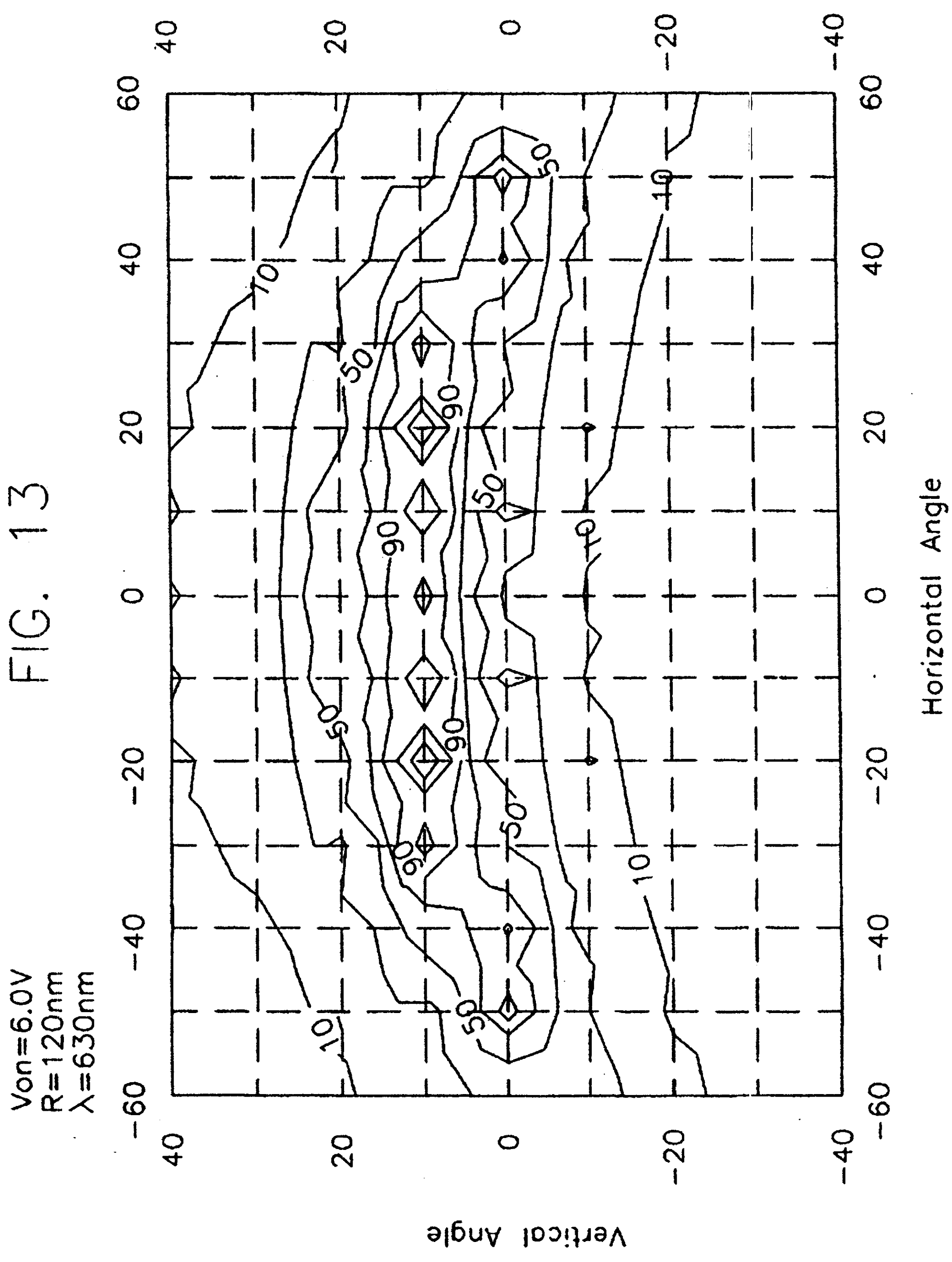


FIG. 12



Von=6.8V
R=120nm
λ=630nm

FIG. 13


Von=6.0V
R=120nm
λ=630nm
Horizontal Angle
Vertical Angle
10
50
90

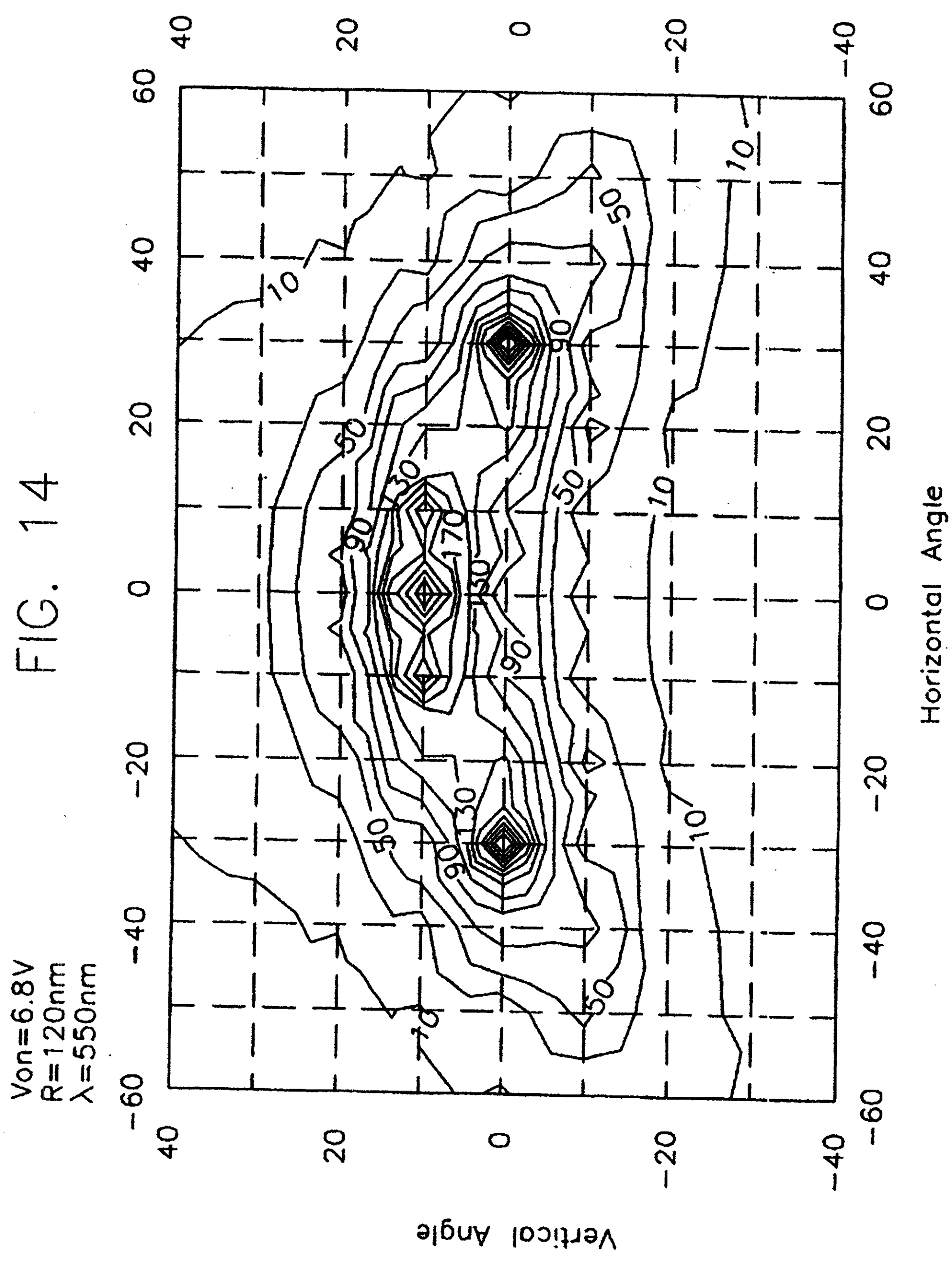

Von=6.8V
R=120nm
λ=550nm
Horizontal Angle
Vertical Angle
10
50
90
130
170

FIG. 14

FIG. 15

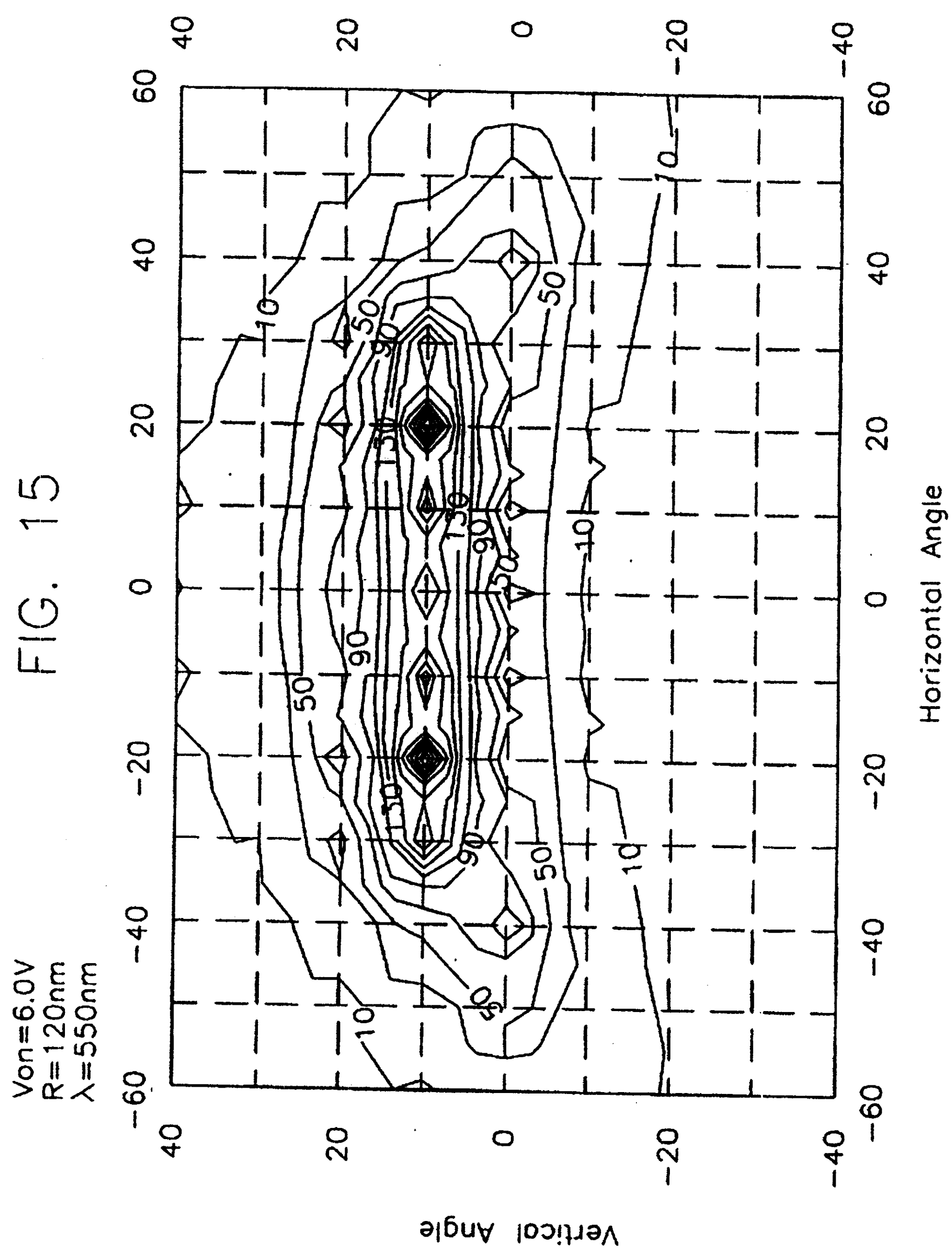


FIG. 16

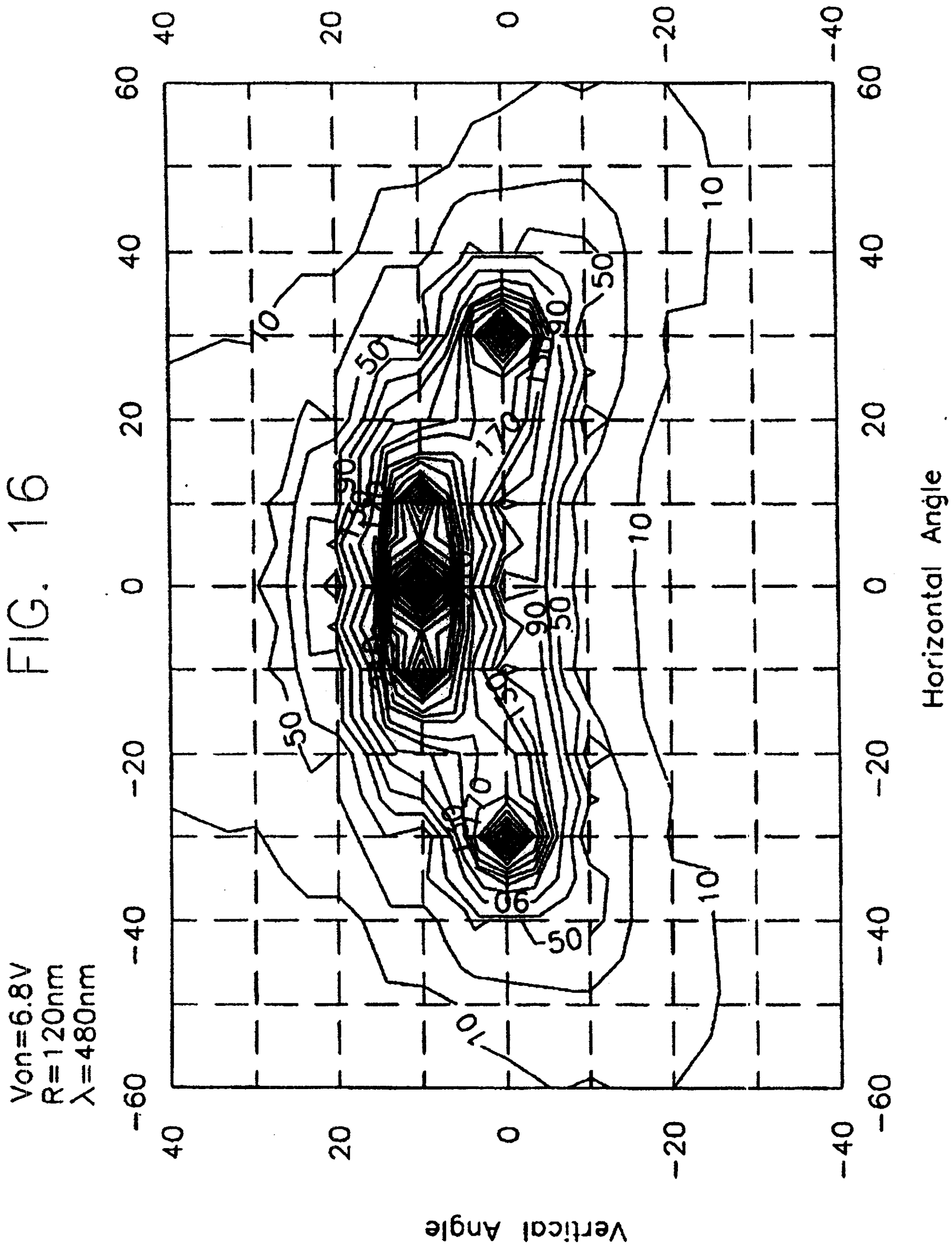


FIG. 17

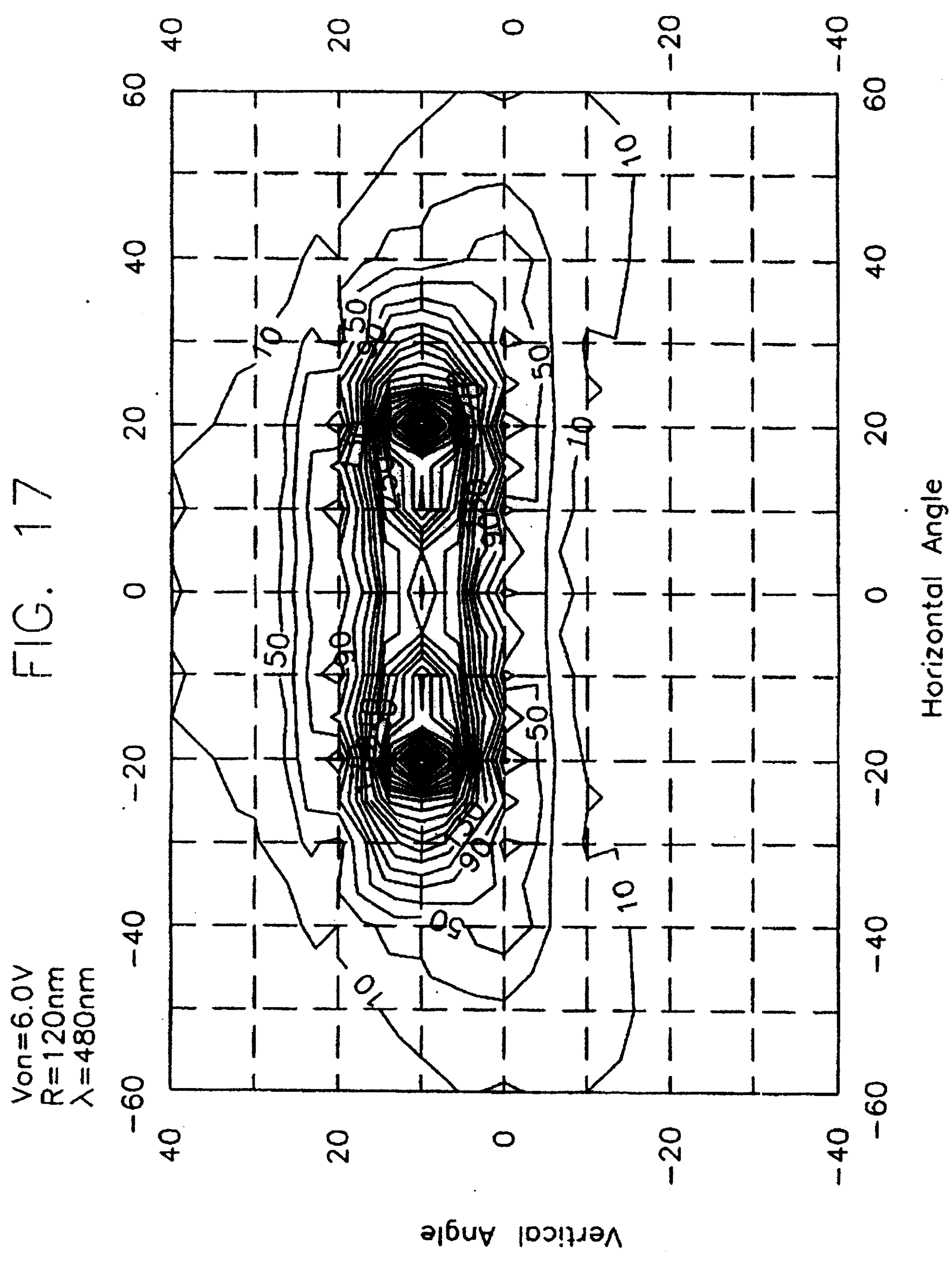

Von=6.0V
R=120nm
λ=480nm
Horizontal Angle
Vertical Angle
-60 -40 -20 0 20 40 60
40 20 0 -20 -40
10
50
70
90

FIG. 18

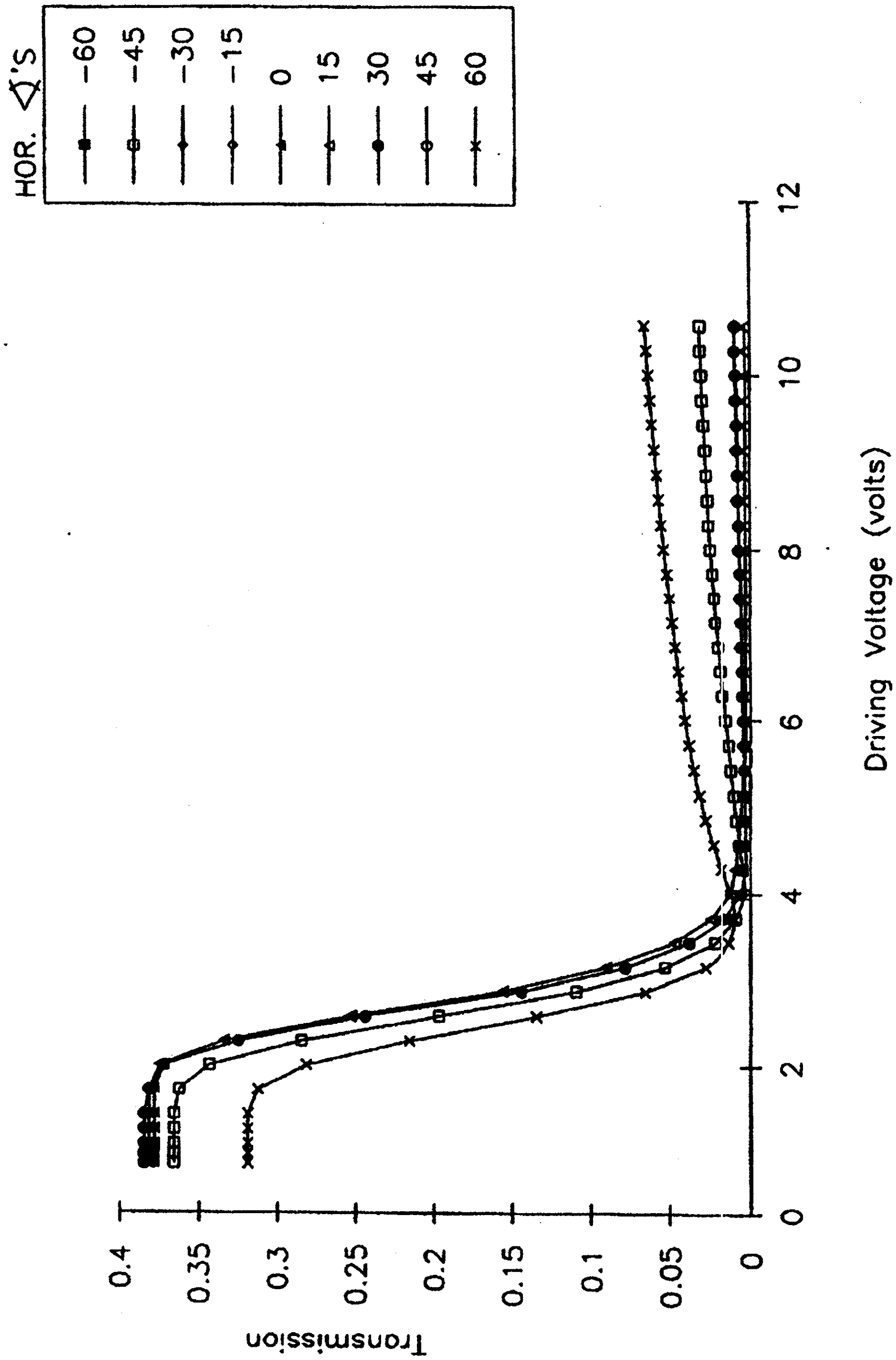

HOR. ∢'S
−60
−45
−30
−15
0
15
30
45
60
Transmission
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Driving Voltage (volts)
0
2
4
6
8
10
12

FIG. 19

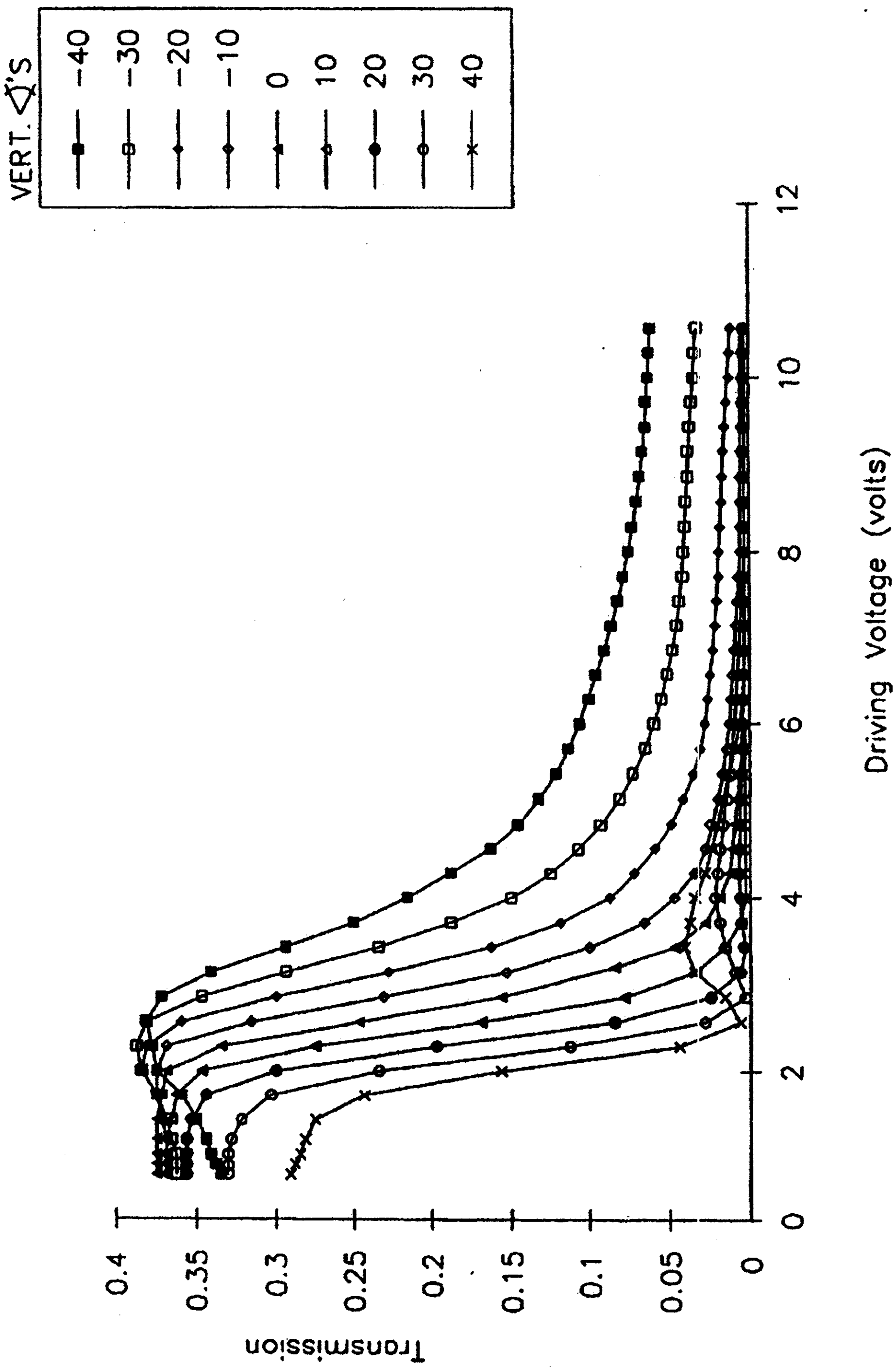

VERT. ∢'S
−40
−30
−20
−10
0
10
20
30
40
Transmission
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Driving Voltage (volts)
0
2
4
6
8
10
12

FIG. 20

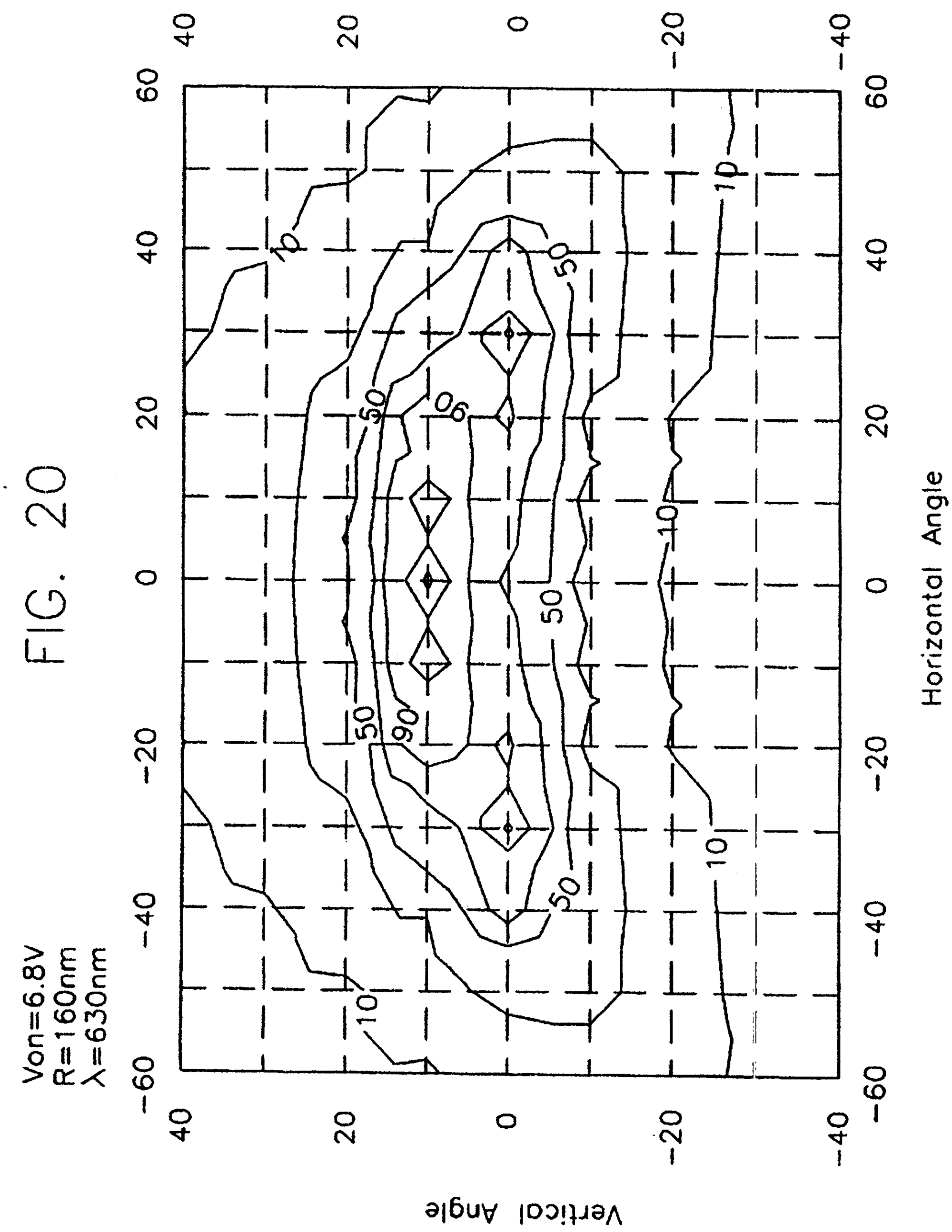
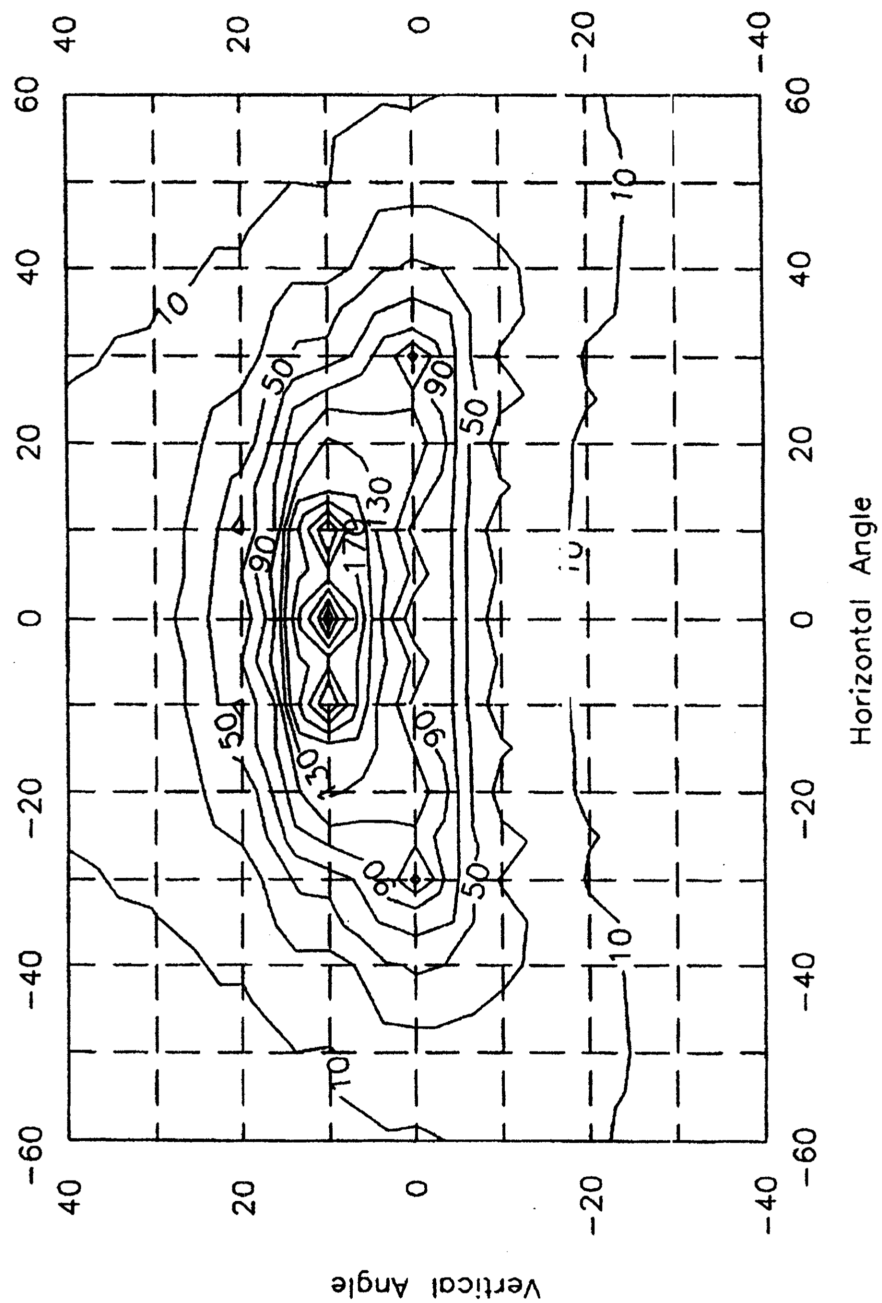

Von=6.8V
R=160nm
λ=630nm
Horizontal Angle
Vertical Angle
10
50
90
−60
−40
−20
0
20
40
60

FIG. 21



Von=6.8V
R=160nm
λ=550nm

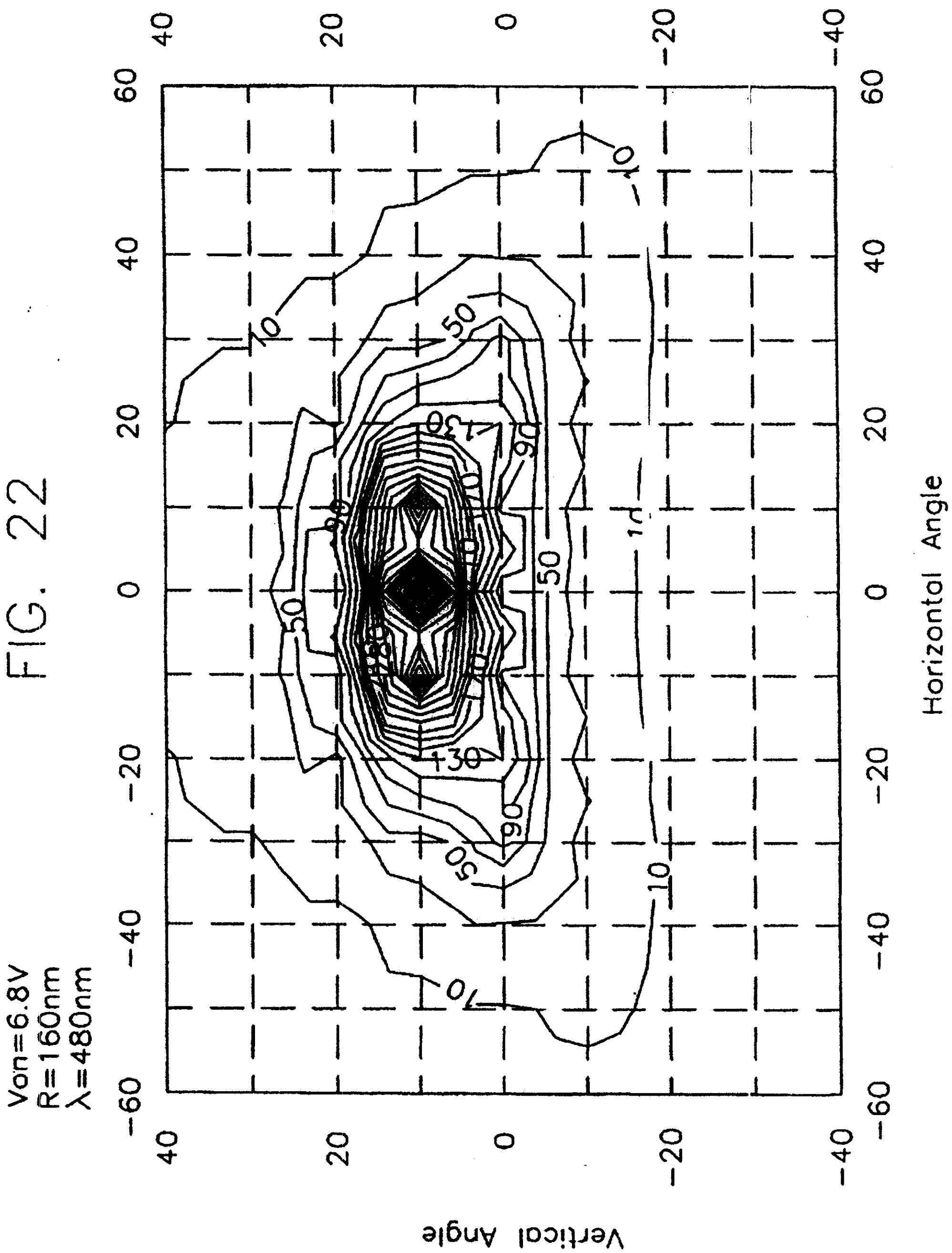


FIG. 22

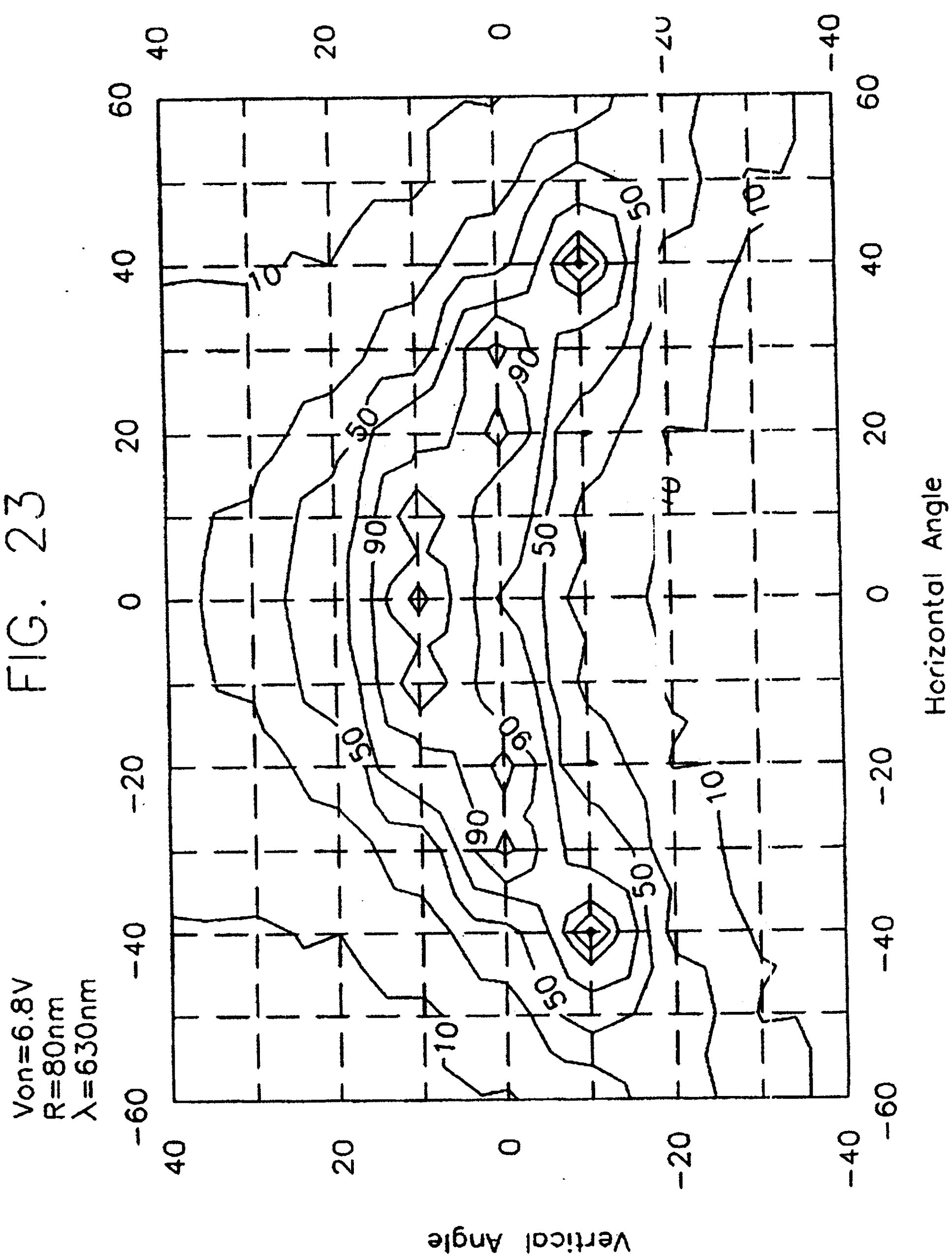


FIG. 23

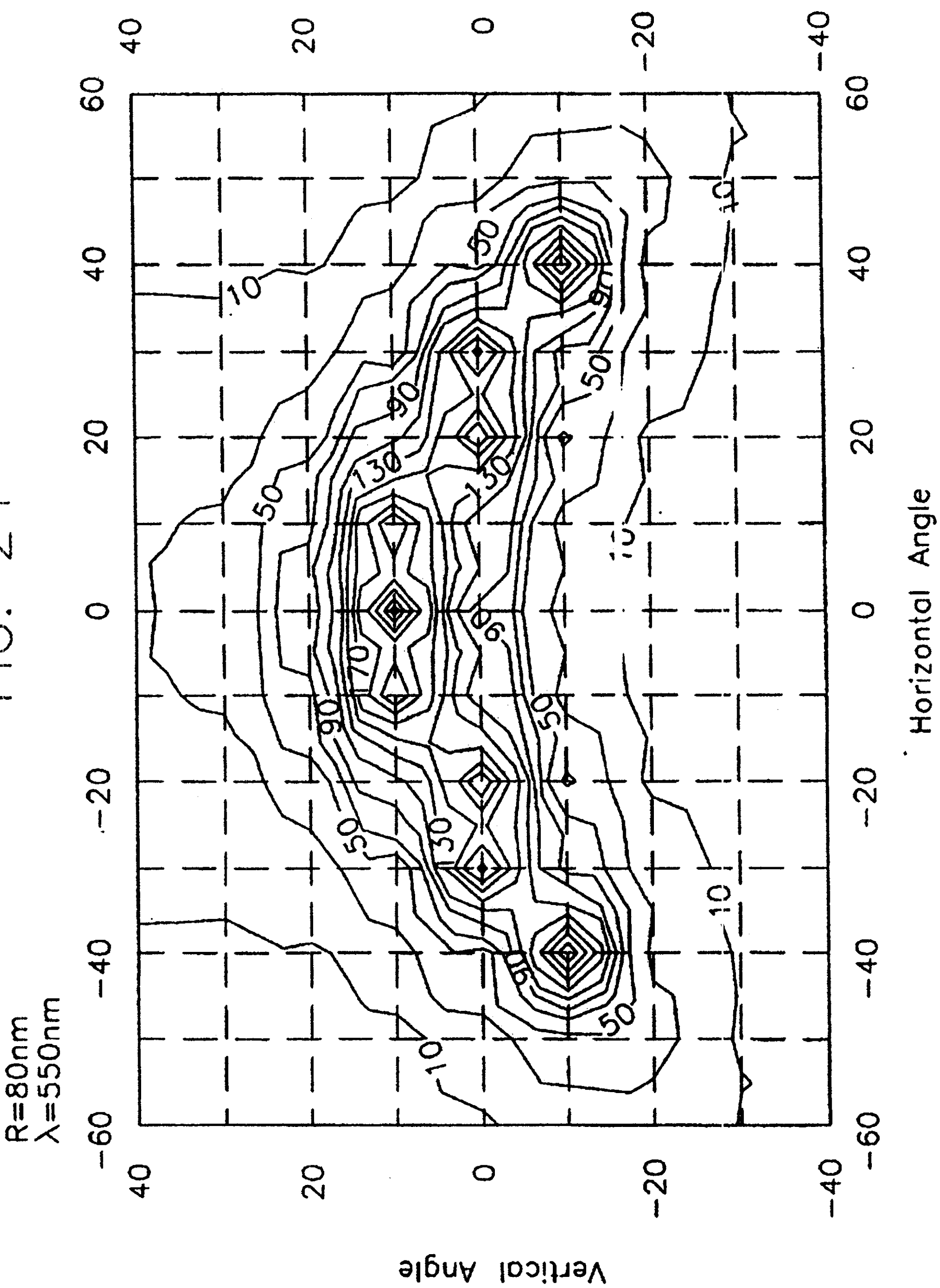


FIG. 24

FIG. 25

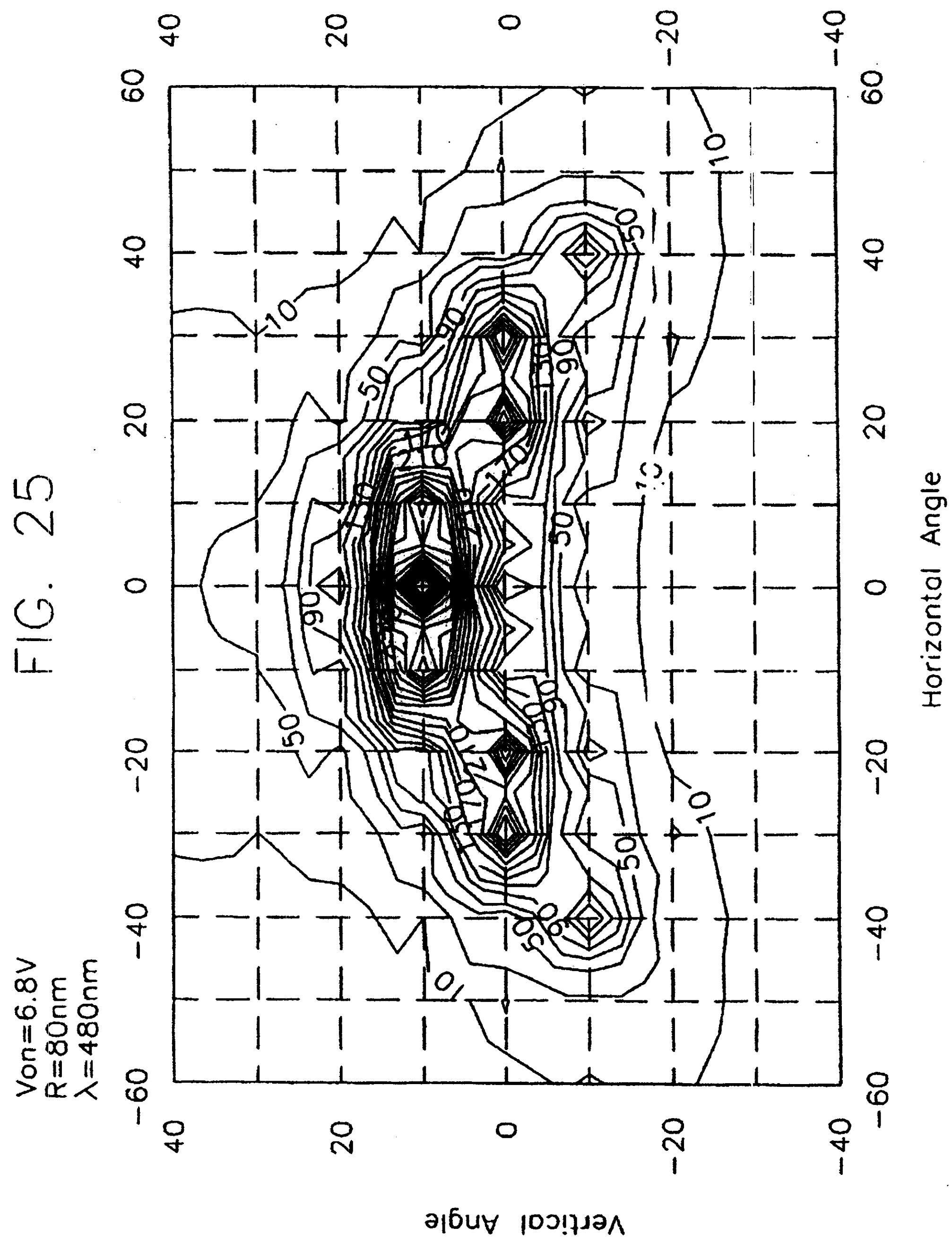


FIG. 26

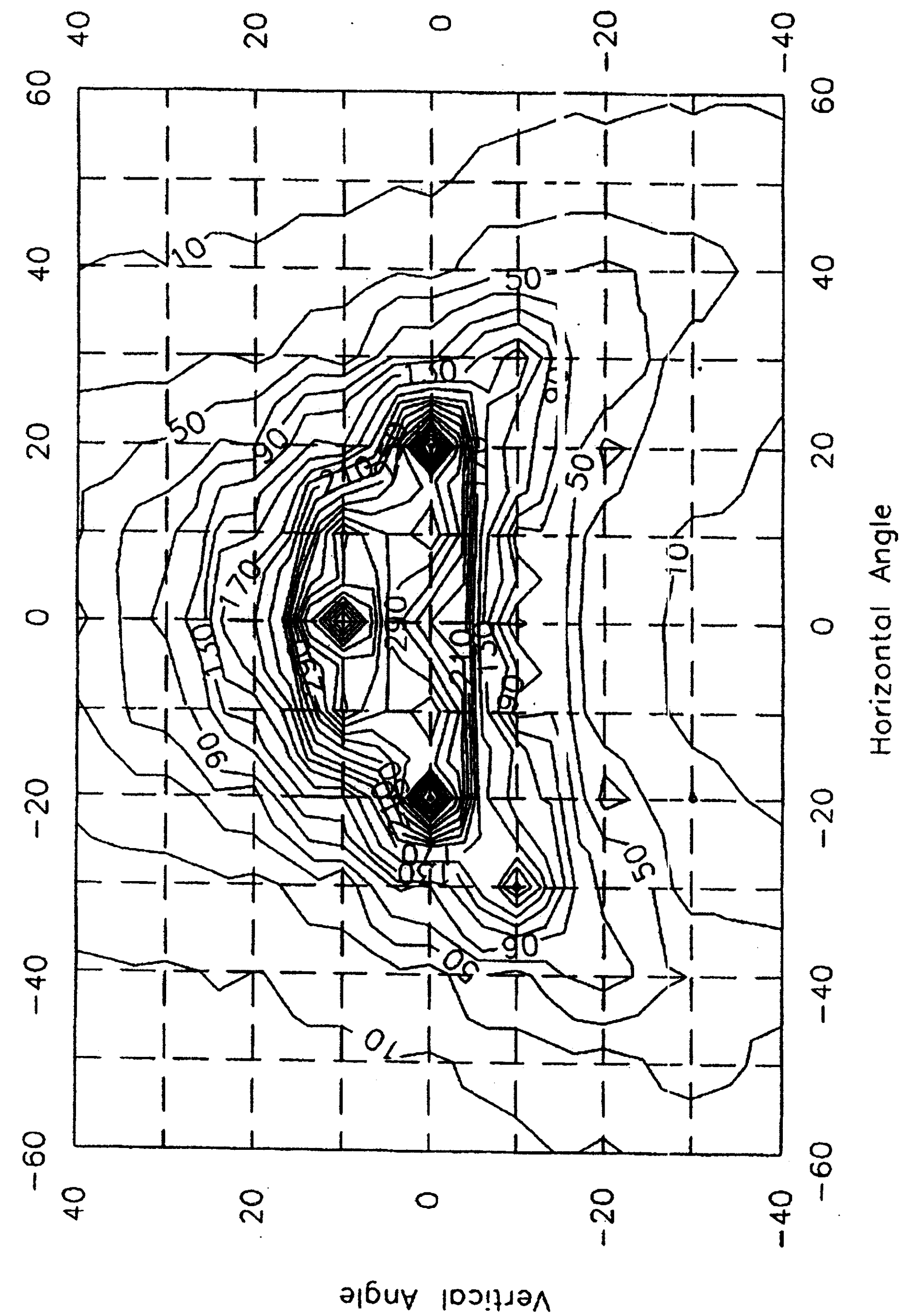

Von=6.8V
R=120nm
λ=WHITE
Horizontal Angle
Vertical Angle
10
50
90
130
170
210
60
40
20
0
-20
-40
-60

FIG. 27

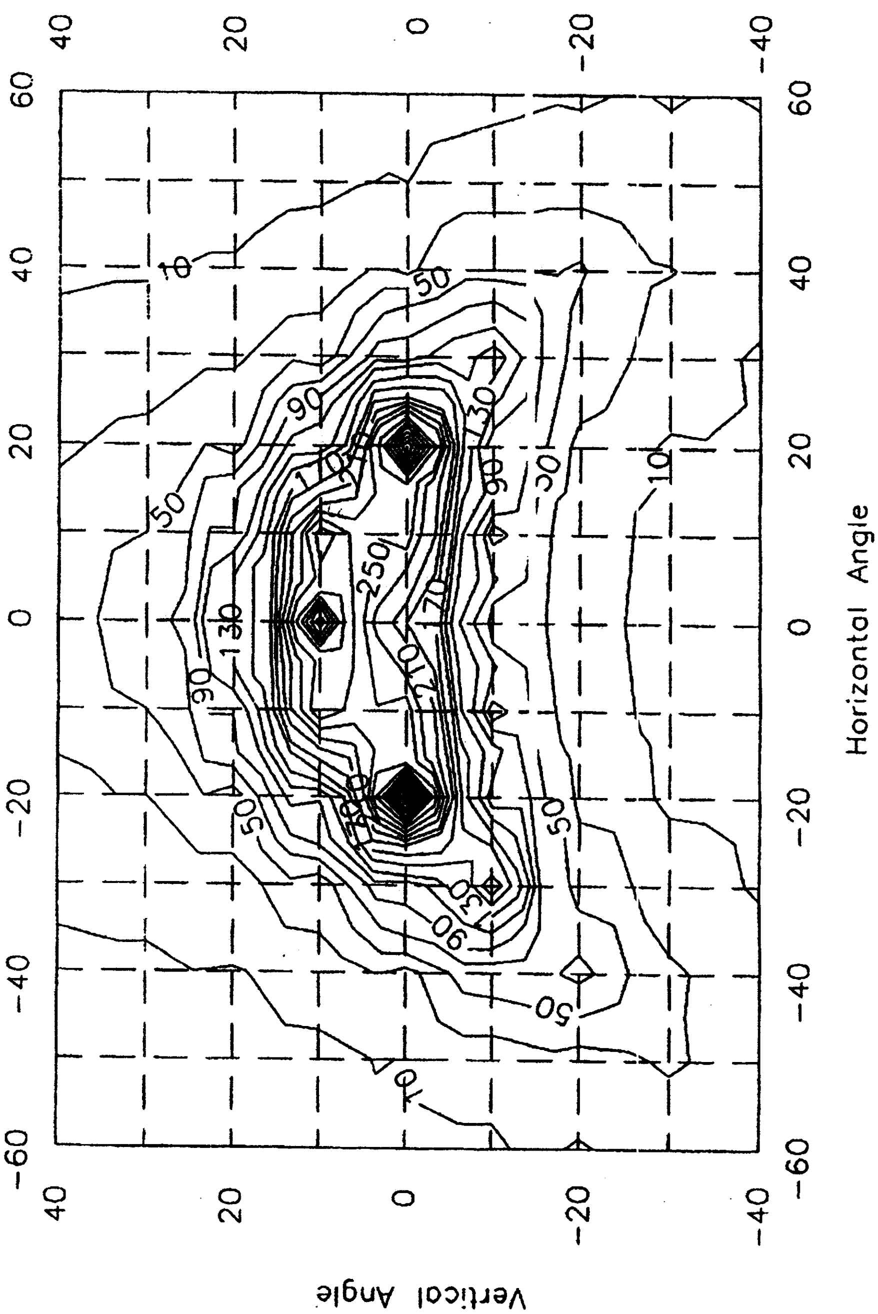
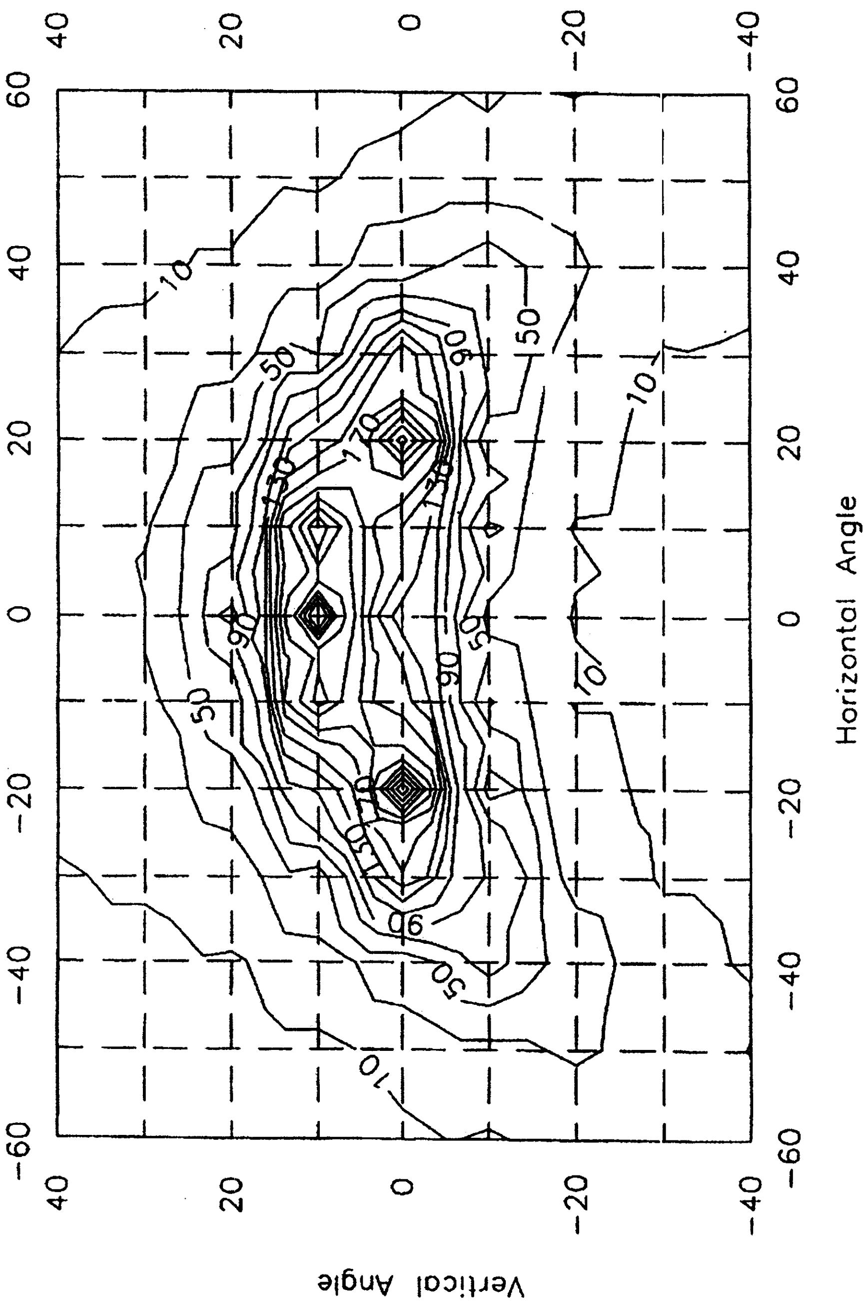


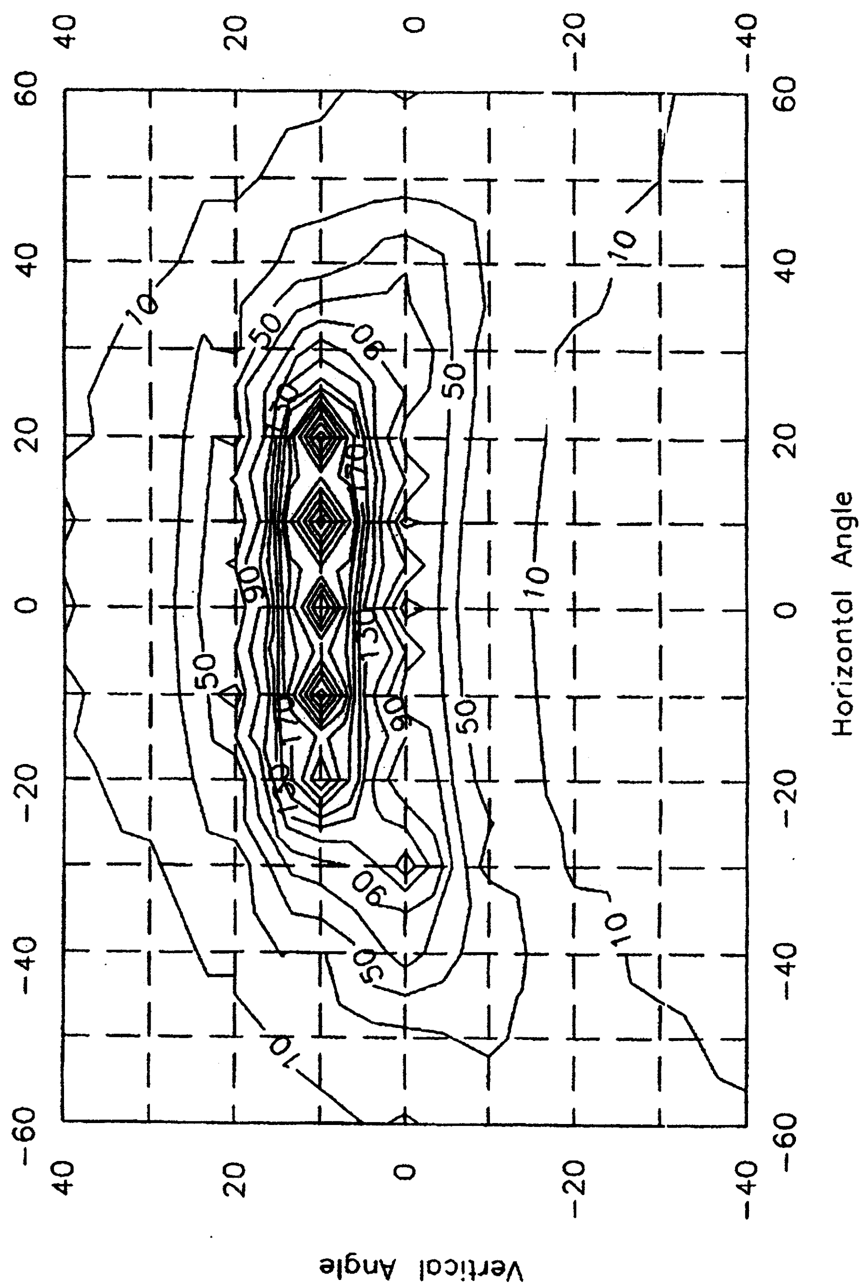
FIG. 28



Von=5.0V
R=120nm
λ=WHITE

FIG. 29

Von=4.0V
R=120nm
λ=WHITE



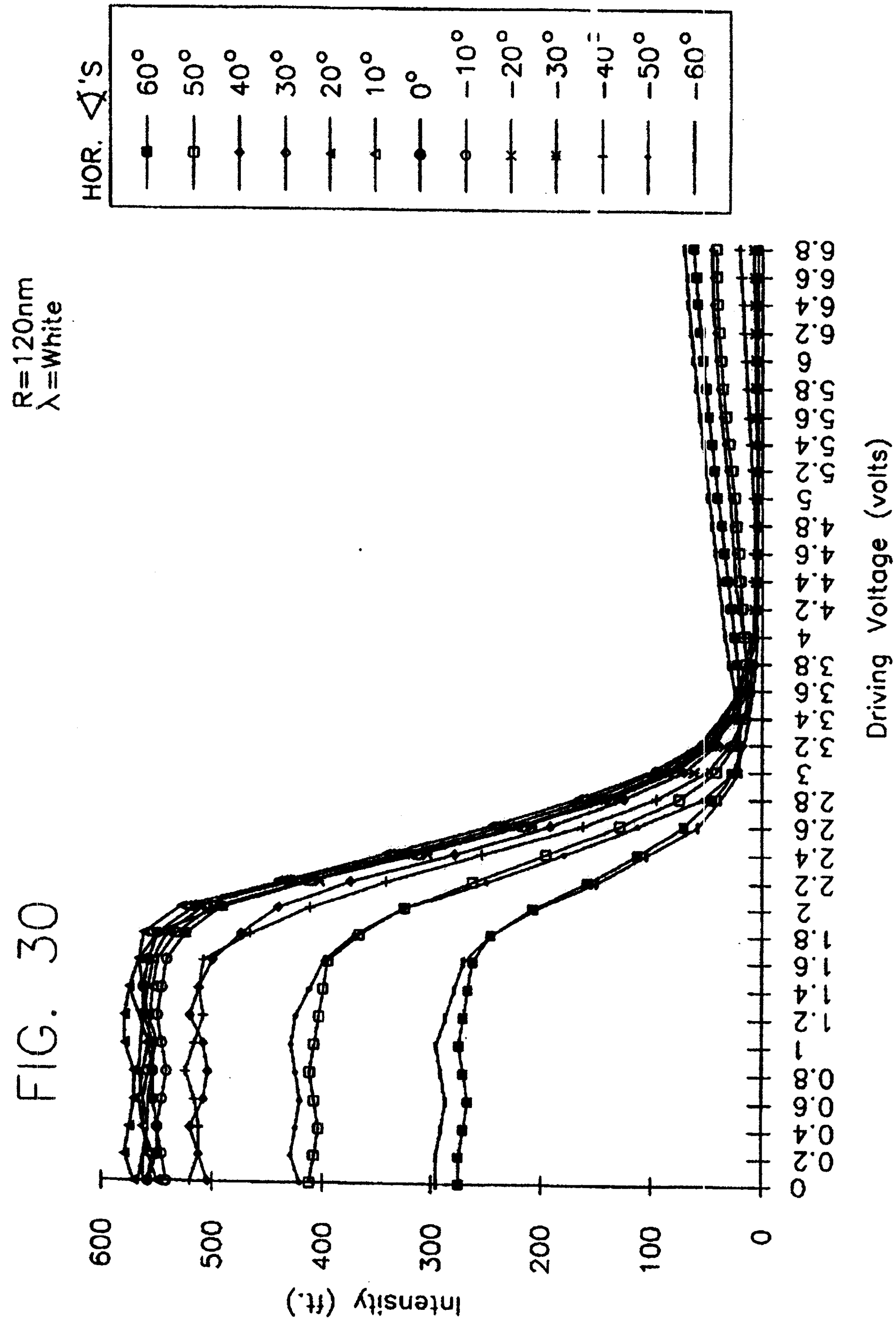

R=120nm
λ=White
HOR. ∢'S
60°
50°
40°
30°
20°
10°
0°
−10°
−20°
−30°
−40°
−50°
−60°
Intensity (ft.)
600
500
400
300
200
100
0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3 3.2 3.4 3.6 3.8 4 4.2 4.4 4.6 4.8 5 5.2 5.4 5.6 5.8 6 6.2 6.4 6.6 6.8
Driving Voltage (volts)

FIG. 30

FIG. 31

Von=6.8V
R=120nm
λ=WHITE

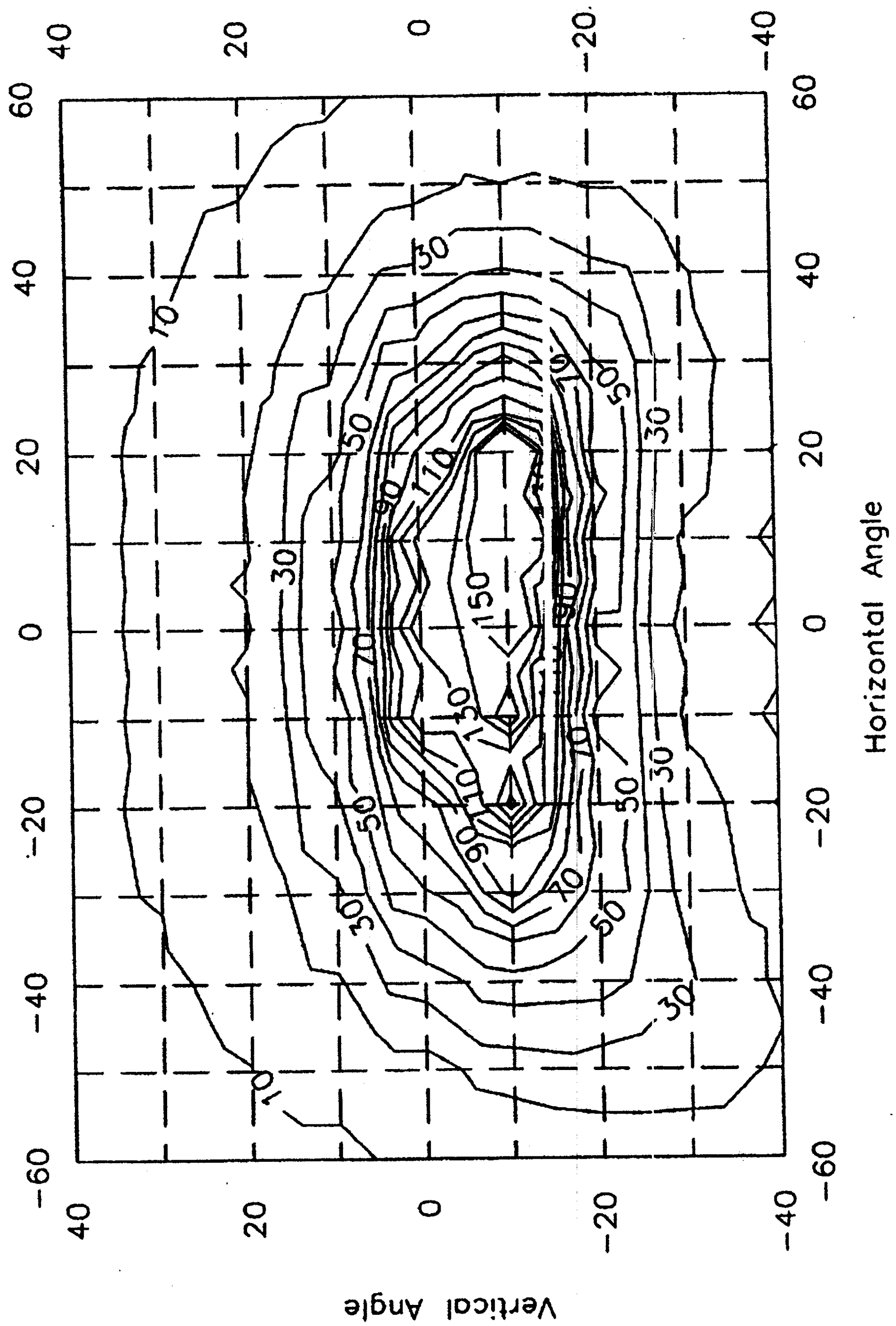
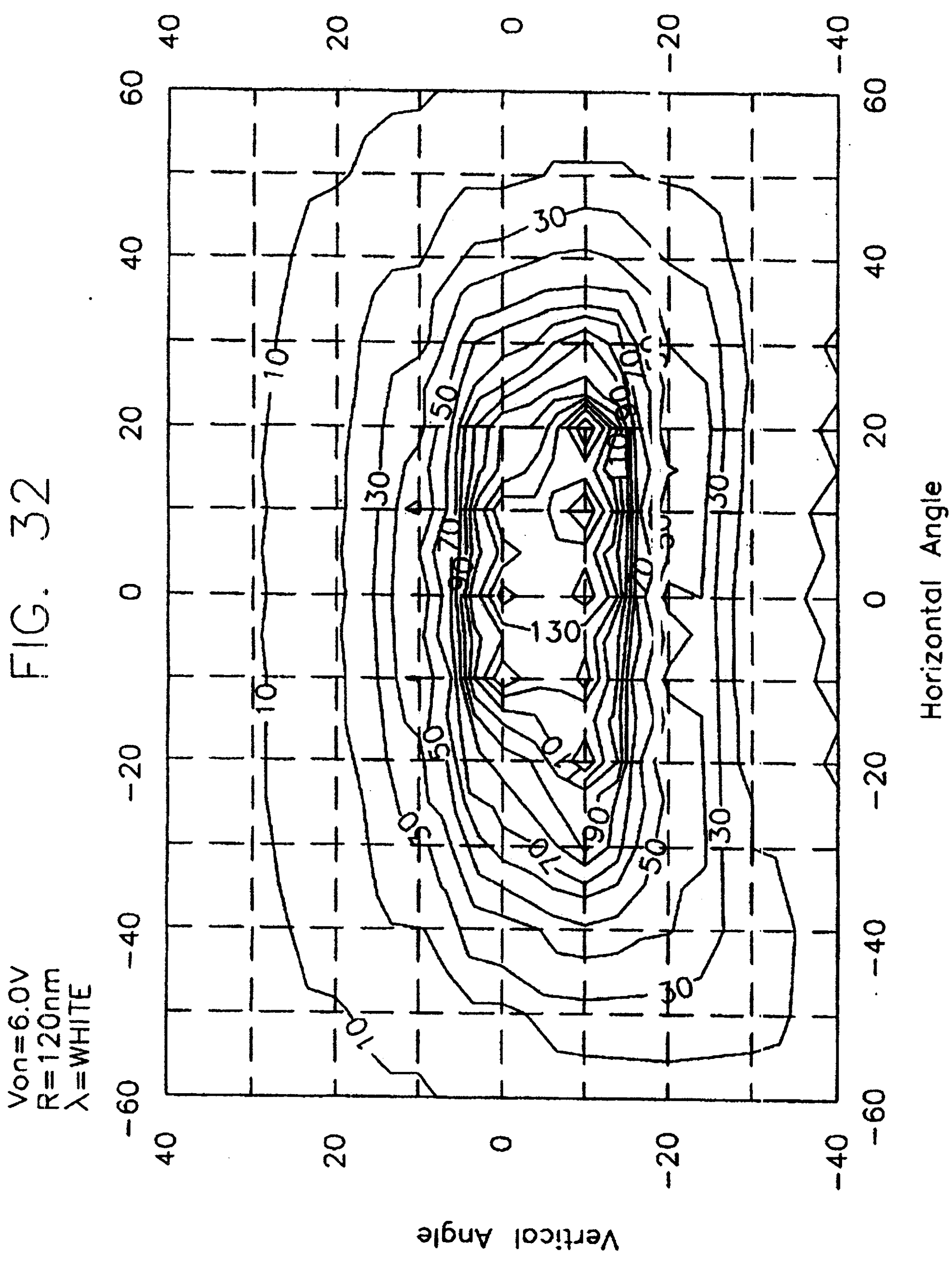


FIG. 32


Von=6.0V
R=120nm
λ=WHITE
Horizontal Angle
Vertical Angle
10
30
50
70
90
110
130

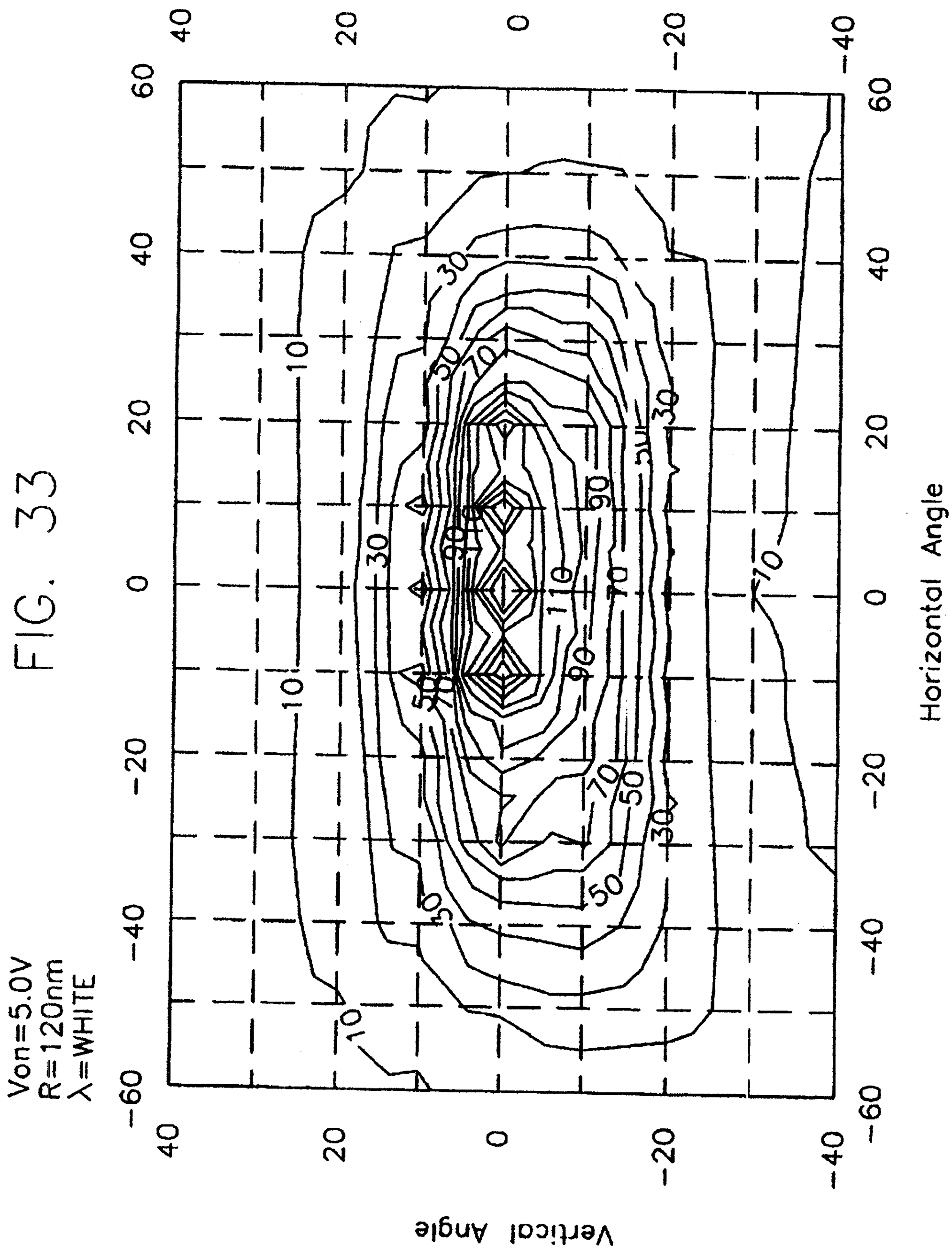


FIG. 33

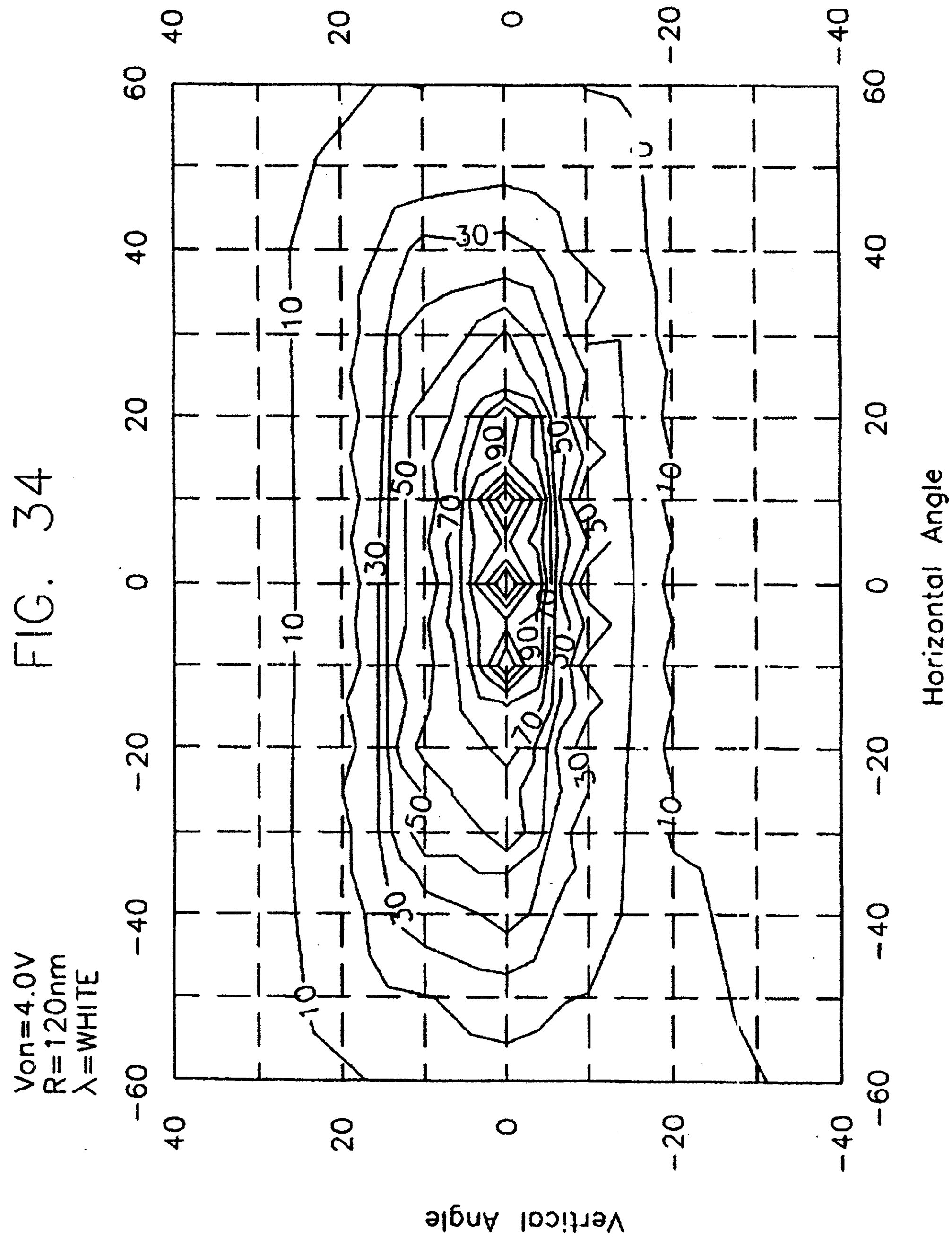

Von=4.0V
R=120nm
λ=WHITE
Horizontal Angle
Vertical Angle
10
30
50
70
90

FIG. 34

FIG. 35

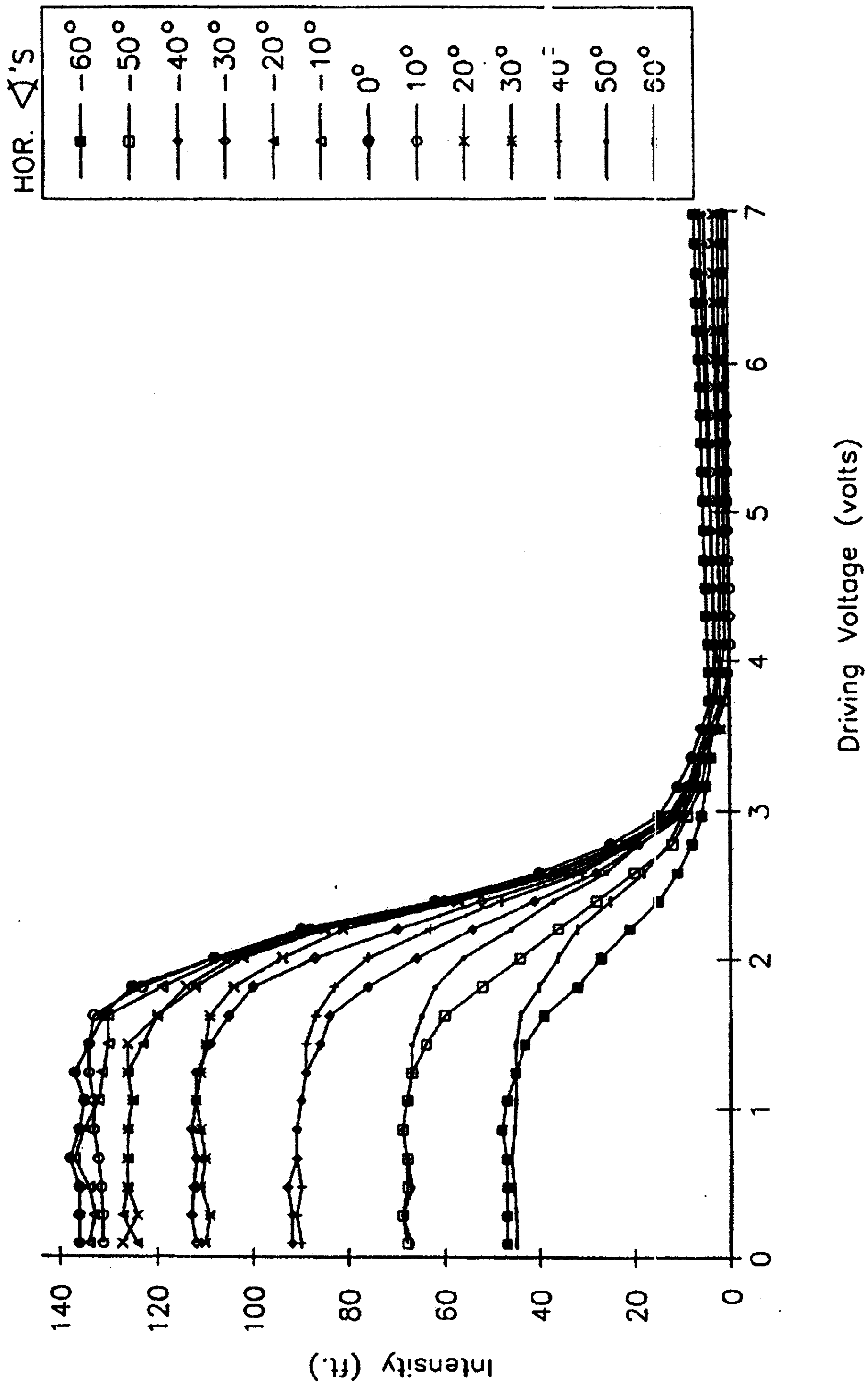
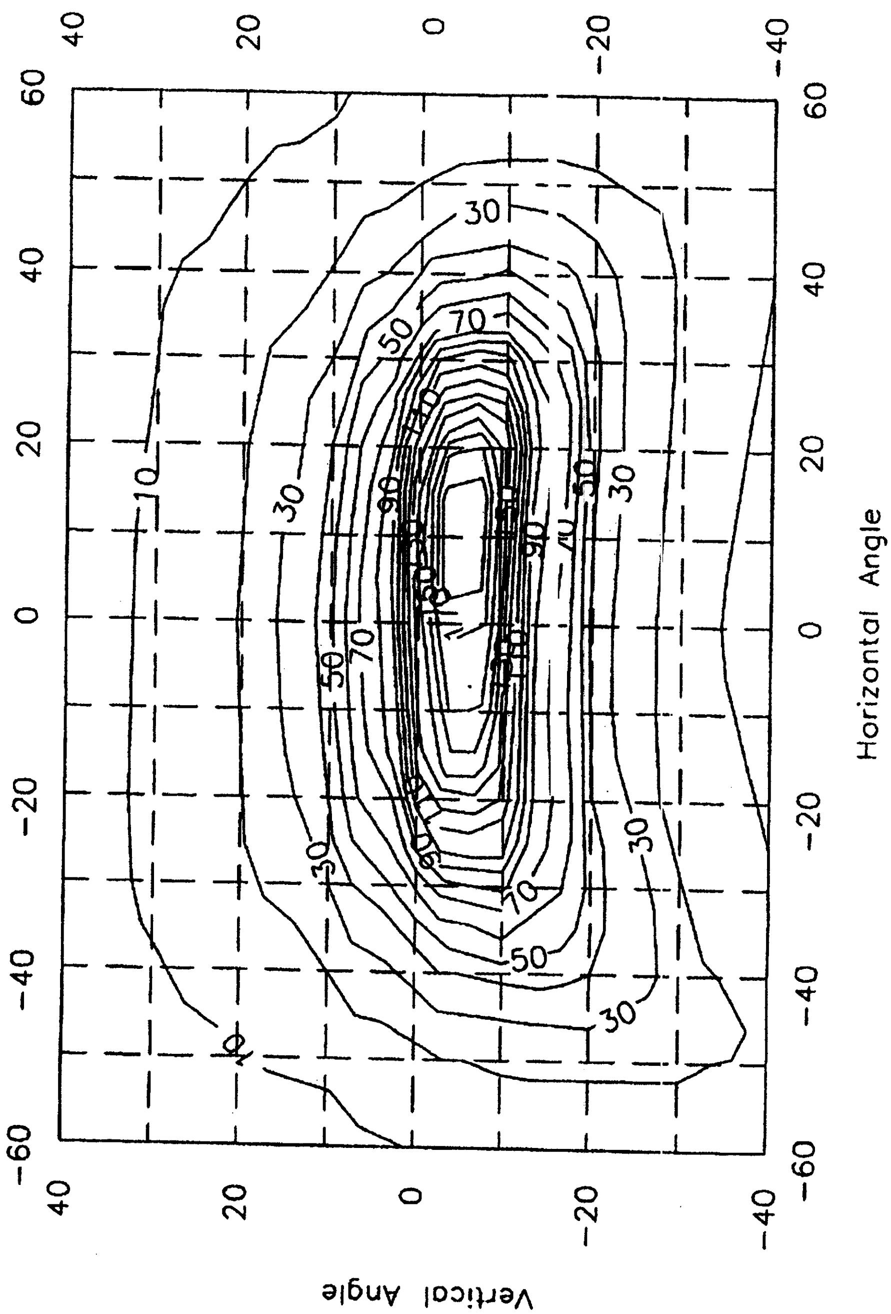

R=120nm
λ =White
HOR. ∢'S
—■— -60°
—□— -50°
—♦— -40°
—◇— -30°
—▲— -20°
—△— -10°
—●— 0°
—○— 10°
—×— 20°
—✱— 30°
—+— 40°
—— 50°
—— 60°
Intensity (fL)
140
120
100
80
60
40
20
0
Driving Voltage (volts)
0
1
2
3
4
5
6
7

FIG. 36



Von=6.0V
R=120nm
λ=WHITE

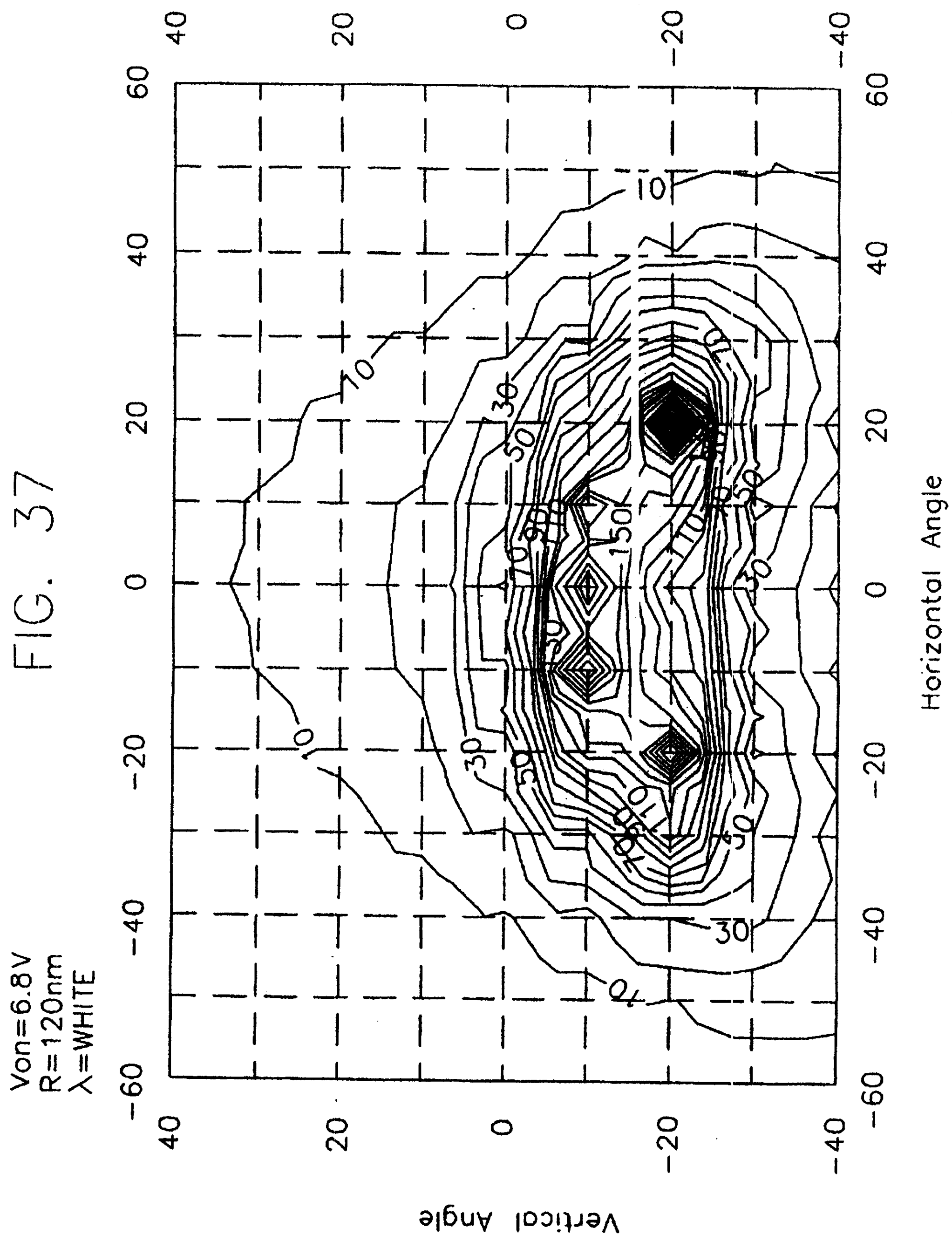

Von=6.8V
R=120nm
λ=WHITE
Horizontal Angle
Vertical Angle
60
40
20
0
−20
−40
−60
10
30
50
70
90
110
130
150

FIG. 37

FIG. 38A

Von=5.0V
R=120nm
λ=WHITE

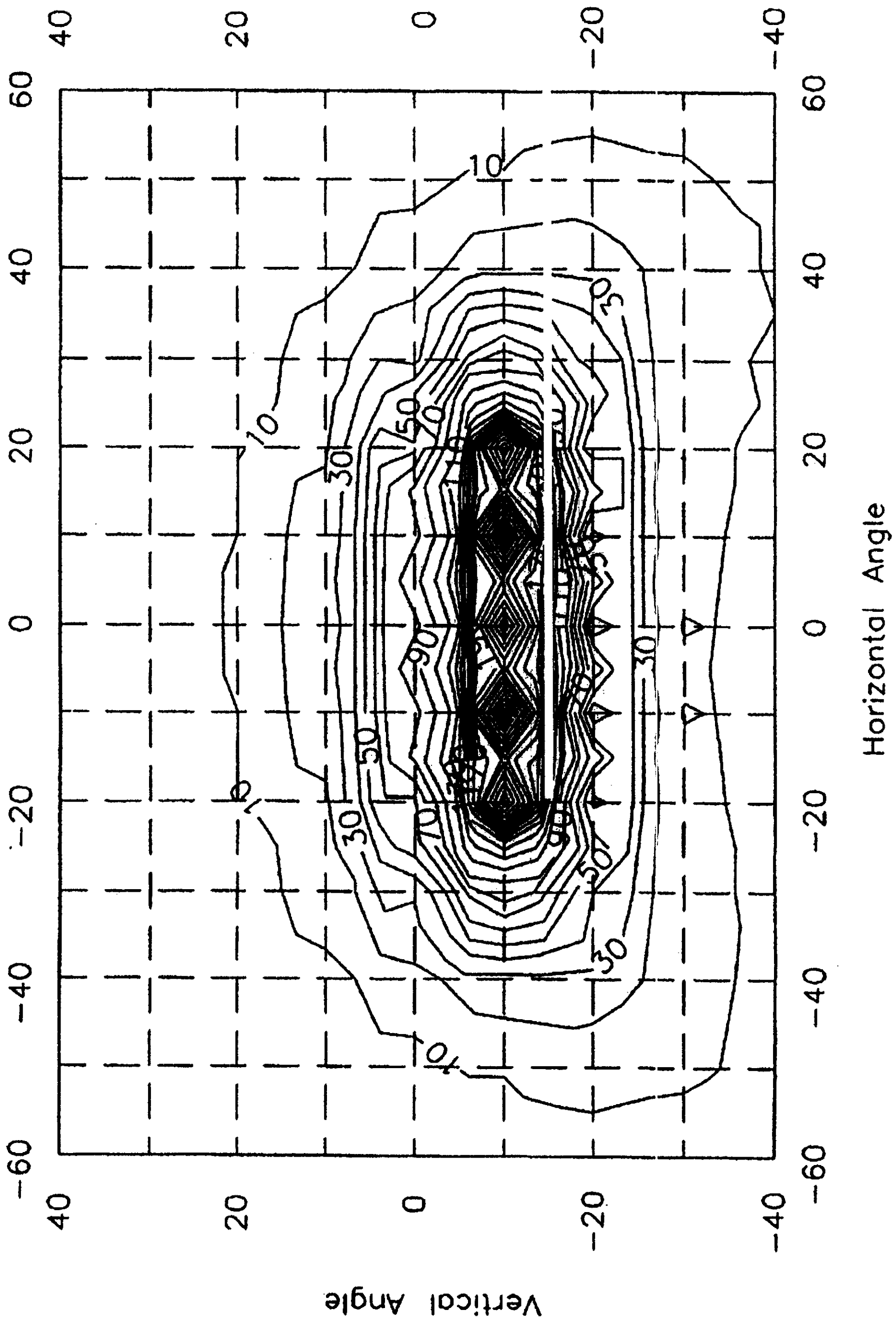


FIG. 38B

R=120nm
λ =White

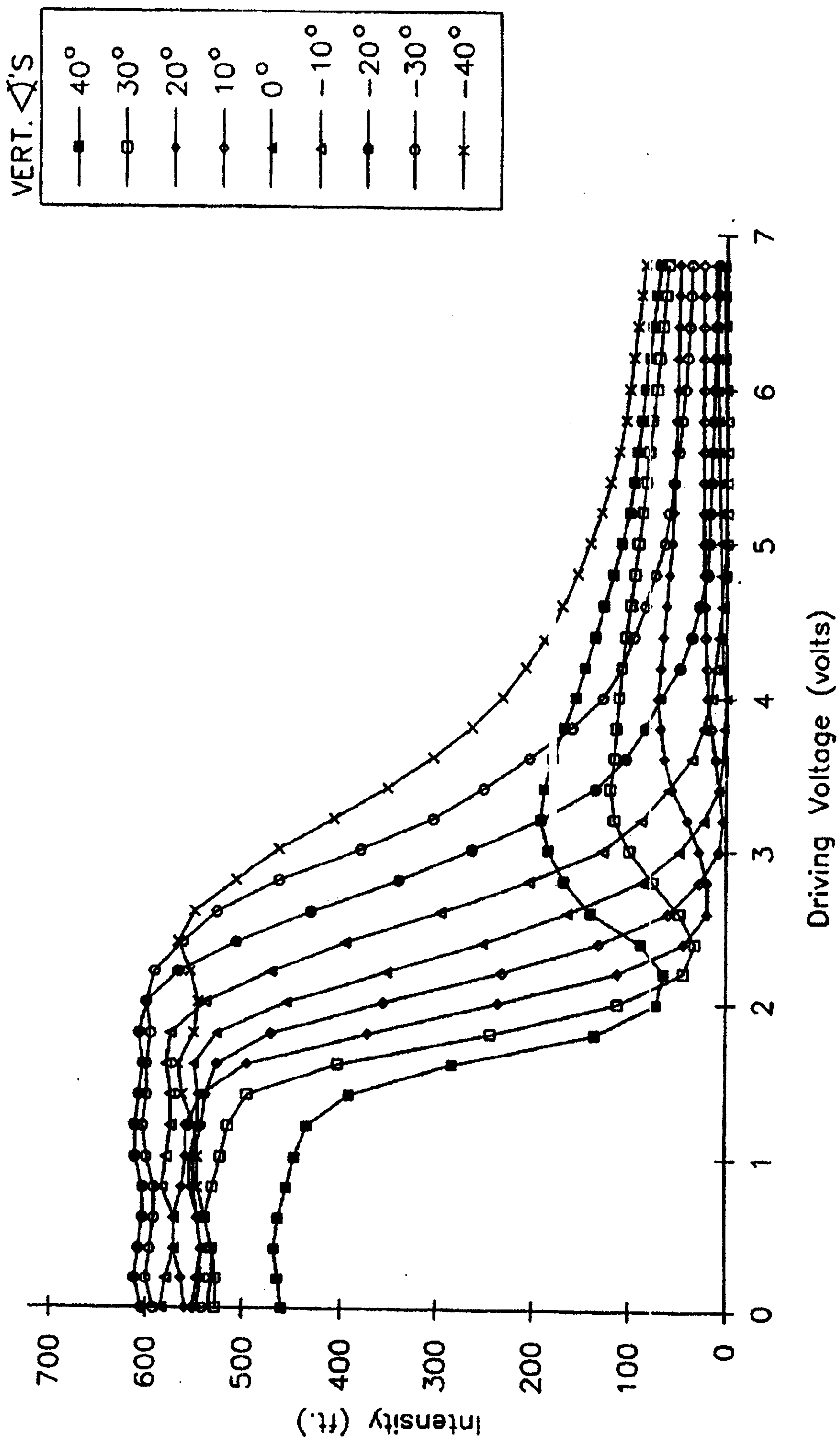
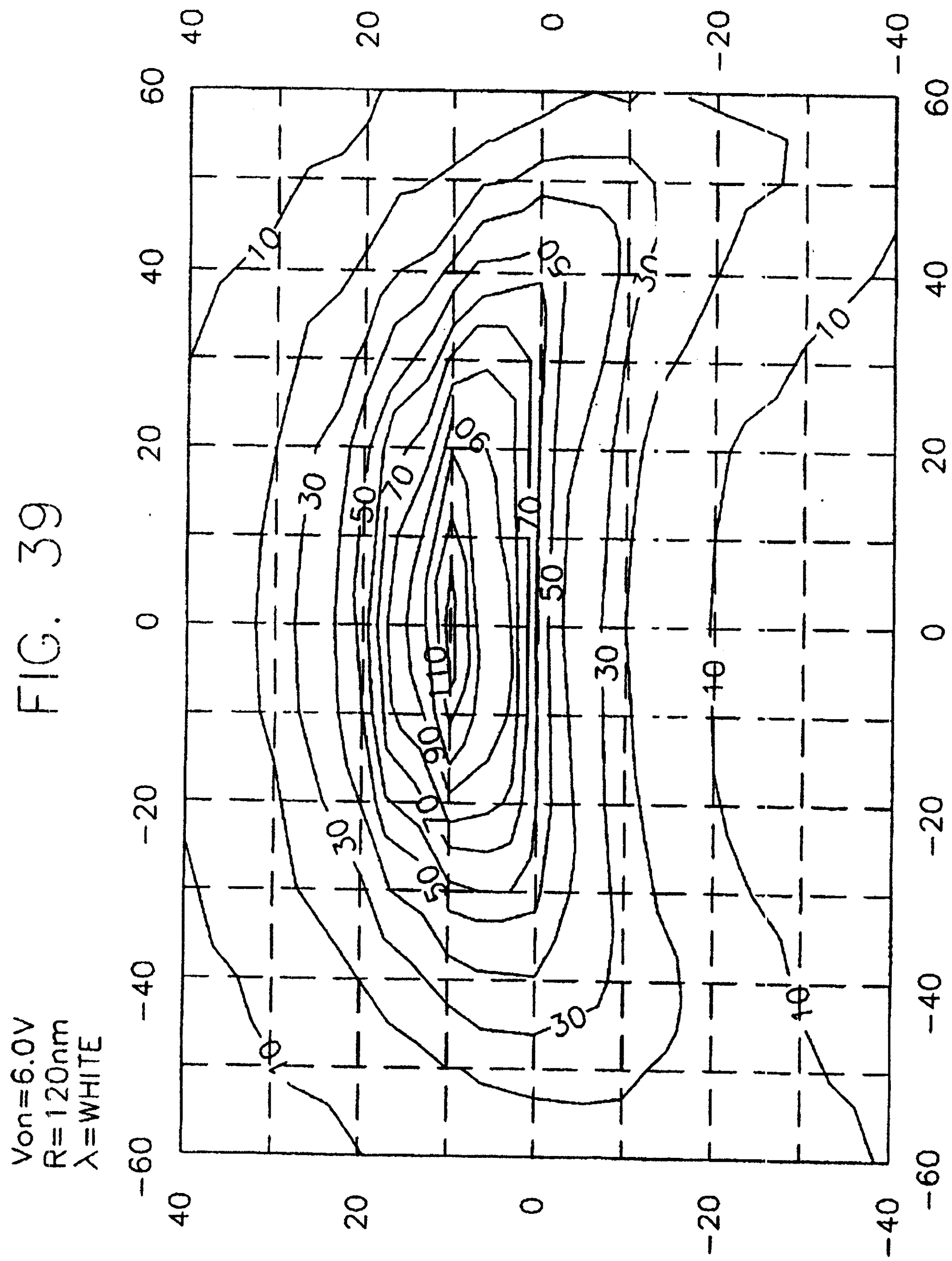


FIG. 39



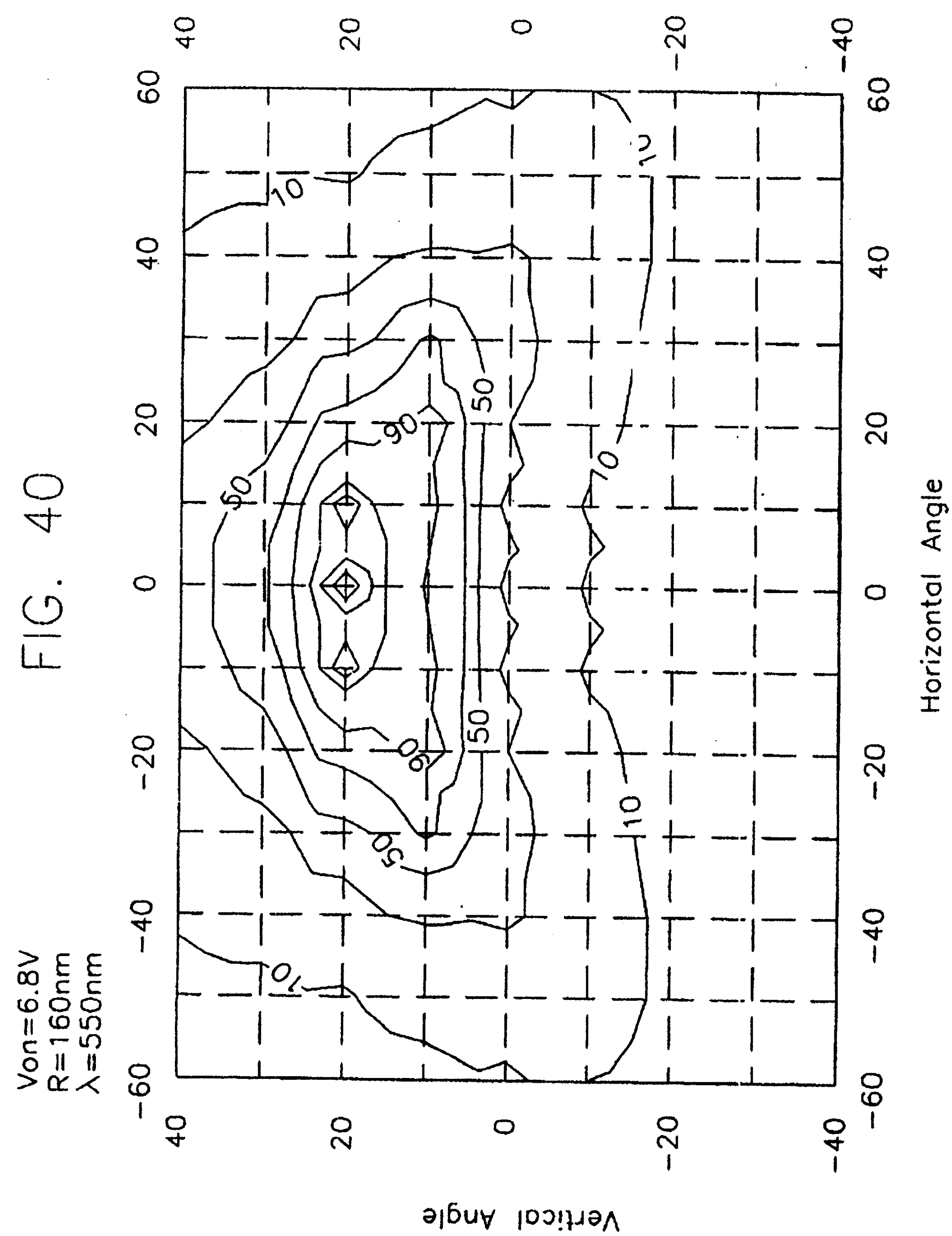
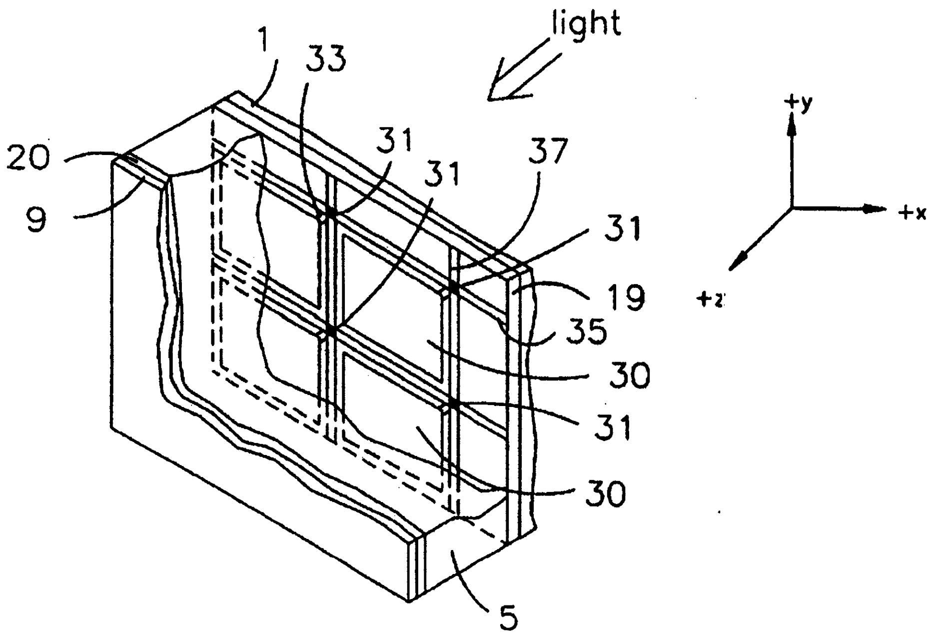

Von=6.8V
R=160nm
λ=550nm
Horizontal Angle
Vertical Angle
10
50
90
70

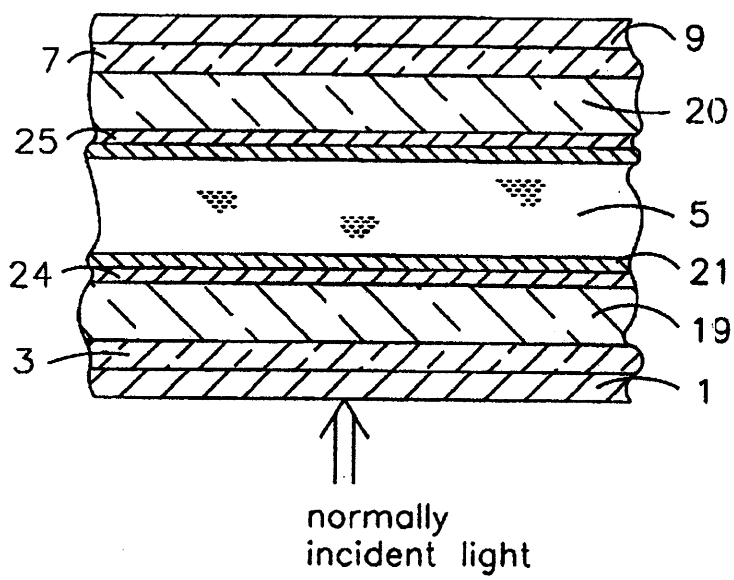
FIG. 40

Fig. 42



light
1
33
20
9
31
31
37
31
19
35
30
31
30
5
+y
+x
+z

Fig. 41



9
7
20
25
5
24
21
19
3
1
normally
incident light

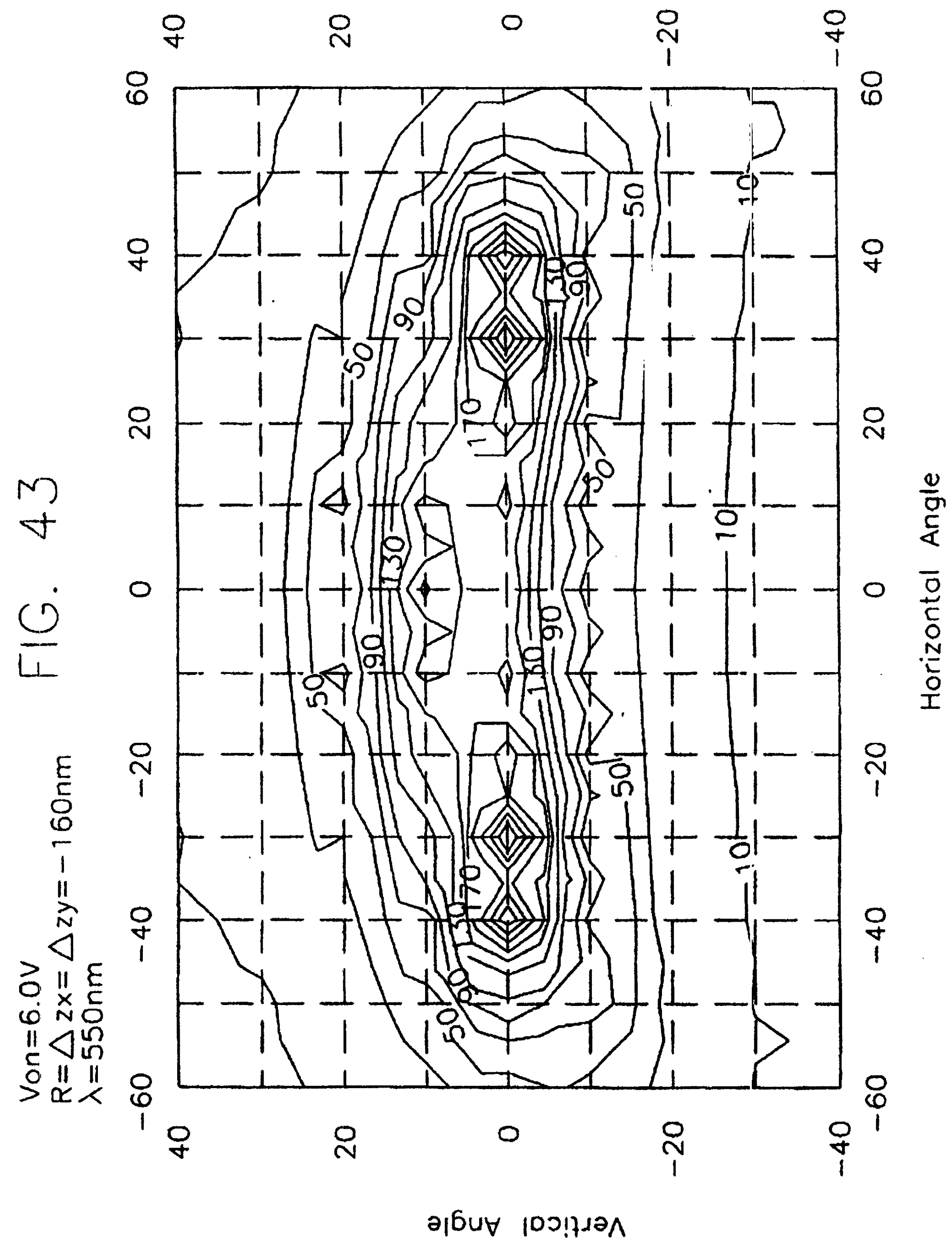
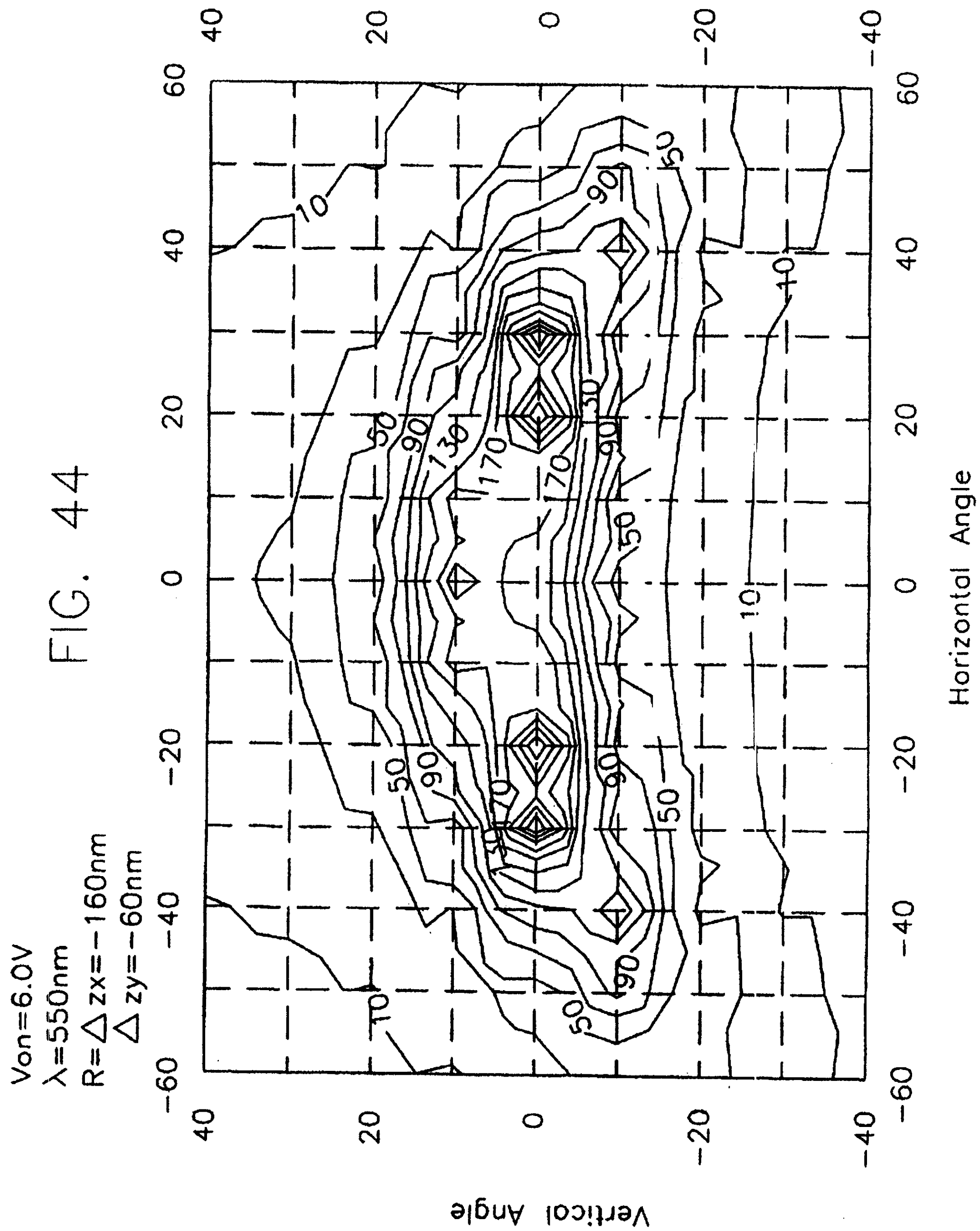

Von=6.0V
R=△zx=△zy=−160nm
λ=550nm
Horizontal Angle
Vertical Angle
−60
−40
−20
0
20
40
60
40
20
0
−20
−40
10
50
90
130
170

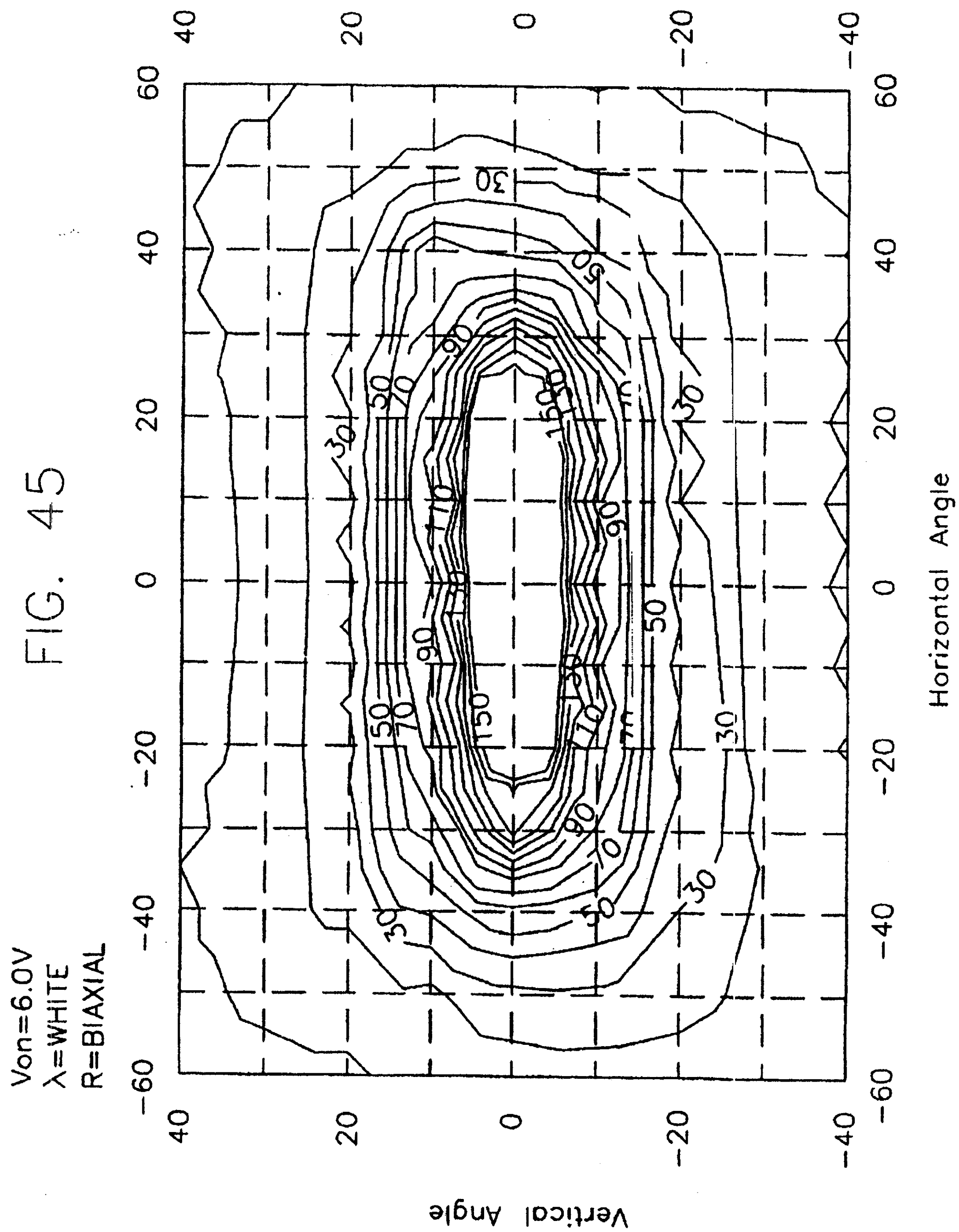
FIG. 43

FIG. 44



Von=6.0V
λ=550nm
R=△zx=−160nm
△zy=−60nm
Horizontal Angle
Vertical Angle
10
50
90
130
170

FIG. 45



LCD INCLUDING A NEGATIVE BIAXIAL RETARDER ON EACH SIDE OF THE LIQUID CRYSTAL LAYER

This application is a continuation of Ser. No. 08/711,797, filed Sep. 10, 1996, which is a continuation of Ser. No. 08/167,652, filed Dec. 15, 1993, (now U.S. Pat. No. 5,570,214), the disclosures of which are incorporated herein by reference.

This invention relates to a liquid crystal display having at least two retardation films, one on each side of a liquid crystal layer. More particularly, this invention relates to a normally white liquid crystal display which includes at least one retardation film having a retardation value of 80–200 nm on each side of the liquid crystal layer.

BACKGROUND OF THE INVENTION

Liquid crystal materials are useful for electronic displays because light traveling through a layer of liquid crystal (LC) material is affected by the anisotropic or birefringent value (ΔN) of the material, which in turn can be controlled by the application of a voltage across the liquid crystal material. Liquid crystal displays are desirable because the transmission or reflection of light from an external source, including ambient light and backlighting schemes, can be controlled with much less power than .was required for the illuminance materials used in other previous displays. Liquid crystal displays (LCDs) are now commonly used in such applications as digital watches, calculators, portable computers, avionic cockpit displays, and many other types of electronic devices which utilize the liquid crystal display advantages of long-life and operation with low voltage and power consumption.

The information in many liquid crystal displays is presented in the form of a matrix array of rows and columns of numerals or characters, which are generated by a number of segmented electrodes arranged in such a matrix pattern. The segments are connected by individual leads to driving electronics, which apply a voltage to the appropriate combination of segments to thereby display the desired data and information by controlling the light transmitted through the liquid crystal material. Graphic information in, for example, avionic cockpit applications or television displays may be achieved by a matrix of pixels which are connected by an X-Y sequential addressing scheme between two sets of perpendicular conductor lines (i.e. row and column lines). More advanced addressing schemes use arrays of thin film transistors, diodes, MIMS, etc. which act as switches to control the drive voltage at the individual pixels. These schemes are applied predominantly to twisted nematic liquid crystal displays, but are also finding use in high performance versions of super twisted liquid crystal displays.

Contrast is one of the most important attributes determining the quality of both normally white (NW) and normally (NB) liquid crystal displays. Contrast, or the contrast ratio, is the difference between OFF state transmission versus ON state transmission. In normally black liquid crystal displays, the primary factor limiting the contrast achievable in these LCDs is the amount of light which leaks through the display in the darkened or OFF state. In normally white (NW) LCDs, the primary factor limiting the contrast is the amount of light which leaks through the display in the darkened or ON state. These problems are compounded in a bright environment, such as sunlight, where there is a considerable amount of reflected and scattered ambient light. In color liquid crystal displays, light leakage causes severe color

shifts for both saturated and gray scale colors. These limitations are particularly important for avionic applications, where the copilot's viewing of the pilot's displays is important.

In addition, the legibility of the image generated by both normally black (NB) and normally white (NW) liquid crystal display devices depends on the viewing angle, especially in the matrix address device with a large number of scanning electrodes. Absent a retardation film, the contrast ratio of a typical NB or NW liquid crystal display is usually at a maximum only within a narrow viewing (or observing) angle centered about normal incidence (0° horizontal viewing angle and 0° vertical viewing angle) and drops off as the angle of view is increased.

It would be a significant improvement in the art to provide a liquid crystal display capable of presenting a high quality, high contrast image over a wide field of view.

Normally black liquid crystal displays are quite sensitive to cell gap, or the thickness "d" of the liquid crystal material, as well as to the temperature of the liquid crystal material. Therefore, normally black liquid crystal displays must be manufactured in accordance with rather specific tolerance parameters related to the cell gap of the display making them both difficult and expensive to make. One way in which to compensate for the normally black displays high sensitivity to cell gap is to provide such a multi-colored display with a multi-gap design wherein the thickness "d" of the liquid crystal material for each colored subpixel is matched to the first transmission minimum of the color of that subpixel. See, for example, U.S. Pat. No. 4,632,514 which utilizes the multi-gap approach by varying the liquid crystal material thickness "d" for the red, green, and blue subpixels therein so as to match the thickness "d" of each subpixel to the three different transmission minimums representative of the colors red, green, and blue. This increases, of course, the difficulty and expense of manufacturing this type of LCD.

Although a normally black display is rather sensitive to temperature and cell gap "d", a significant advantage associated with this type of liquid crystal display is that it provides good contrast ratios at wide viewing angles. Thus, a viewer may satisfactorily observe the data of the display throughout a wide range of viewing angles. Contrast ratio curves of, for example, 10:1 in normally black displays often extend up to viewing angles of, for example, 0° vertical, ±60° horizontal. The fact that normally black displays have such good contrast ratios at such large horizontal viewing angles enables them to be used in commercial applications where such viewing angles are required or preferred. Furthermore, NB displays generall experience more darkened state leakage than do NW displays.

Turning now to normally White liquid crystal displays, NW displays are fairly insensitive to the temperature and cell gap "d" of liquid crystal material. This allows for the manufacturing tolerances associated with the development of normally white displays to be lessened. Hence, normally white displays are easier and cheaper to manufacture then their normally black counterparts. However, while normally white LCDs are less sensitive to temperature and cell gap than normally black LCDs, their contrast ratios at large viewing angles are generally small relative to those of normally black displays. For example, 10:1 contrast ratio curves in normally white displays often only extend up to horizontal viewing angles of about 0° vertical, ±35° horizontal. This is significantly less than the extent to which the same contrast ratio curves extend horizontally in normally black displays. Therefore, while normally white LCDs are

easier and cheaper to manufacturer than normally black liquid crystal displays, they have a smaller range of satisfactory viewing angles than do normally black displays. It would satisfy a long felt need in the art if one could provide NW display which had good contrast ratios at large viewing angles.

Several types of liquid crystal pixels or cells are in widespread use in flat panel displays. Active matrix addressing allows such displays to present a full color image with high resolution. When viewed directly at a normal or ON axis viewing angle (0° vertical, 0° horizontal viewing angle), a liquid crystal display of either the normally black or normally white type provides a generally high quality output, especially when the cell gap "d" is matched to the first transmission minimum, but the image degrades and contrast ratios decrease at increased viewing angles. This occurs because liquid crystal cells operate by virtue of the anisotropic or birefringent effect exhibited by their liquid crystal layer which includes a large number of anisotropic liquid crystal molecules. Such a material will be positively uniaxially birefringent (i.e., the extraordinary refractive index is larger than the ordinary refractive index). The phase retardation effect such a liquid crystal material has on light passing through it inherently varies or increases with the inclination angle of light, leading to lower contrast ratios and a lower quality image at larger viewing angles. By introducing an optical compensating element (or retarder) into the liquid crystal pixel or cell, however, it is possible to correct for the unwanted angular effects and thereby maintain higher contrast at both normal and larger viewing angles than otherwise possible.

The type and orientation of optical compensation or retardation required depends in part upon the type of display, normally black or normally white, which is used.

In a normally black (NB) twisted nematic display, the twisted nematic liquid crystal material is placed between polarizers whose transmission axes are parallel to one another. In the unenergized OFF state (no voltage above the threshold voltage V_{th} is applied across the liquid crystal material), normally incident light from the backlight is first polarized by the rear polarizer and in passing through the pixel or cell has its polarization direction rotated by the twist angle of the liquid crystal material dictated by the buffing zones. This effect is known as the twisting effect. The twist angle is set, for example, to be about 90° so that the light is blocked or absorbed by the front or output polarizer when the pixel is in the OFF state. When a voltage is applied via electrodes across the normally black pixel, the liquid crystal molecules are forced to more nearly align with the electric field, eliminating the twisted nematic optical effect of the LC material. In this orientation, the optical molecular axes of the liquid crystal layer molecules are perpendicular to the cell walls. The liquid crystal layer then appears isotropic to normally incident light, eliminating the twist effect such that the light polarization state is unchanged by propagation through the liquid crystal layer so that light can pass through the output polarizer. Patterns can be written in a normally black display by selectively applying a variable voltage to the portions of the display which are to appear illuminated.

Turning again to normally white (NW) LCD cells, in a normally white liquid crystal display configuration, a twisted nematic cell preferably having a twist angle of about 80°–100° (most preferably about 90°) is placed between polarizers which have substantially crossed or perpendicular transmission axes, such that the transmission axis of each polarizer is either parallel (P-buffed) or perpendicular (X-buffed) to the buffing direction or orientation of the liquid

crystal molecules in the interface region of the liquid crystal material adjacent each polarizer. In other words, normally white cells can be either P-buffed where both polarizer axes are substantially parallel to their respective adjacent buffing zones, or X-buffed where both polarizer axes are substantially perpendicular to their respective adjacent buffing zones.

This NW orientation of the polarizers reverses the sense of light and dark from that of the normally black displays discussed above. The OFF or unenergized (no applied voltage above V_{th} across the liquid crystal material) areas appear light in a normally white display, while those which are energized appear dark.

The problem of ostensibly dark areas appearing light or colored when viewed at large angles still occurs, however, thereby creating the aforesaid lowered contrast ratios at reasonably large viewing angles. The reason for the reduced contrast ratios at large viewing angles in normally white displays is different than the reason for the problem in normally black displays. In the normally white energized darkened areas, the liquid crystal molecules tend to align with the applied electric field. If this alignment were perfect, all of the liquid crystal molecules in the cell would have their long axes normal to the glass substrate or cell wall. In the energized state, the normal white display appears isotropic to normally incident light, which is blocked by the crossed polarizers, thus, resulting in a darkened pixel or subpixel.

The loss of contrast with increased viewing angles in normally white pixels or displays occurs primarily because the homeotropic livid crystal layer does not appear isotropic to OFF axis or OFF normal light. Light directed at OFF normal angles through the liquid crystal material propagates in two modes due to the anisotropy or birefringence (ΔN) of the liquid crystal layer, with a phase delay between these modes which increases with the incident angle of light. This phase dependence on the incident angle introduces an ellipticity to the polarization state which is then incompletely extinguished by the front or exit polarizer in the normally white cell, giving rise to light leakage. Because of the normally white symmetry the birefringence has no azimuthal dependence.

Accordingly, what is needed in normally white displays is an optical compensating or retarding element which introduces a phase delay that restores the original polarization state of the light, allowing the light to be blocked by the output polarizer in the ON state. Optical compensating elements or retarders for normally white displays are known in the art and are disclosed, for example, in U.S. Pat. Nos. 5,184,236; 5,196,953; 5,138,474; and 5,071,997, the disclosures of which are hereby incorporated herein by reference. It is known that the polyimides and copolyimides disclosed by aforesaid U.S. Pat. No. 5,071,997 can be used as negative birefringent retarding elements in normally white liquid crystal displays and are said to be custom tailorable to the desired negative birefringent values without the use of stretching. The polyimide retardation films of No. 5,071,997 are uniaxial but with an optical axis oriented in the Z direction which is perpendicular to the plane defined by the film.

Quite often, the retardation films or plates used in conjunction with normally white displays have a negative birefringent value. However, in certain cases, retardation films, having a positive birefringent value are used in combination with such normally white cells. An example of this is U.S. Pat. No. 5,184,236 which will be discussed more fully below.

FIG. 1 is a contrast ratio curve graph for a prior art normally white light valve pixel. The light valve for which the contrast ratio curves are illustrated in FIG. 1 includes a rear polarizer having a transmission axis defining a first direction, a front or exit polarizer having a transmission axis defining a second direction wherein the first and second directions are substantially perpendicular to one another, a liquid crystal material having a cell gap "d" of 5.86 µm, a rear buffing zone oriented in the second direction, and a front buffing zone orientated in the first direction. The temperature was 34.4° C. when the graph illustrated by FIG. 1 was plotted. This light valve pixel did not include a retarder. The above-listed parameters with respect to FIG. 1 are also applicable to FIGS. 2 and 3.

The contrast ratio graph of FIG. 1 was plotted utilizing a 6.8 V driving voltage V_{ON}, and a 0.2 volt V_{OFF}. As can be seen in FIG. 1, the 10:1 contrast ratio curve extends along the 0° vertical viewing axis only to angles of about −40° horizontal and +38° horizontal. Likewise, the 30:1 contrast ratio curve extends along the 0° vertical viewing axis only to horizontal angles of about ±30°. This graph is illustrative of the problems associated with normally white liquid crystal displays in that their contrast ratios at large horizontal and vertical viewing angles are fairly low.

FIG. 2 is a contrast ratio curve graph for the normally white light valve described above with respect to FIG. 1. However, the FIG. 2 graph was plotted utilizing a V_{ON} of 5.0 volts and a V_{OFF} of 0.2 volts. Again, the temperature was 34.4° C. As can be seen by comparing the graphs of FIG. 1 and FIG. 2, as the voltage applied to the liquid crystal material decreases, as in FIG. 2, the contrast ratio curves expand horizontally and contract vertically. The 10:1 contrast ratio curve of FIG. 2 along the 0° vertical viewing axis extends a total of about 85° as opposed to only 78° in FIG. 1. Also, the 30:1 contrast ratio curve of FIG. 2 along the 0° vertical viewing axis extends horizontally about 67° as opposed to only about 58° in FIG. 1. With respect to vertical viewing angles, the contrast ratio curves of 10:1 and 30:1 in FIG. 2 do not extend along the 0° horizontal viewing axis to the negative vertical extent that they did in FIG. 1. Accordingly, while the normally white light valve of FIGS. 1–3 has less than desirable contrast ratios at large viewing angles, the contrast ratios expand horizontally and contract vertically as the voltage across the liquid crystal material decreases.

FIG. 3 is a driving voltage versus intensity plot for the light valve pixel described above with respect to FIGS. 1–2 illustrating the gray level characteristics of the pixel. The various curves represent horizontal viewing angles from −60° to +60° along the 0° vertical viewing axis.

Gray level performance of a liquid crystal display is very important. Conventional liquid crystal displays utilize anywhere from about eight to sixty-four different driving voltages. The different driving voltages are referred to as "gray level" voltages. The intensity of the light transmitted through the pixel or display depends upon the driving voltage. Accordingly, gray level voltages are used to generate different shades of different colors and to create different colors when these shades are mixed with one another. Preferably, the higher the driving voltage in a NW display, the lower the intensity of light transmitted therethrough. Likewise then, the lower the driving voltage, the higher the intensity of light emitted from the preferred forms of a normally white display. The opposite is true in a normally black display. Thus, by utilizing multiple gray level driving voltages, one can manipulate either an NW or NB liquid crystal display pixel to emit a desired intensity of light. A gray level V_{ON} is any voltage greater than V_{th} up to about 5.0–6.5 V.

Gray level intensity performance for LCDs is dependent upon the displays' driving voltage. It is desirable in gray level performance of NW displays to have an intensity versus driving voltage curve wherein the intensity of the light emitted from the pixel continually and monotonically decreases as the driving voltage increases. In other words, it is desirable to have gray level performance in a pixel such that the intensity at 6.0 volts is less than that at 5.0 volts, which is in turn less than that at 4.0 volts, which is less than that at 3.0 volts, which is in turn less than that at 2.0 volts, etc. Such good gray level curves across wide ranges of viewing angles allow the intensity of radiation emitted from the pixel to be easily controlled.

Turning again now to FIG. 3, the intensity versus driving voltage curves illustrated therein with respect to the prior art light valve pixel of FIGS. 1–2 having no retardation film are undesirable because of the inversion hump present in the area of the curves having voltages greater than about 3.2 volts. The term "inversion hump" means that the intensity aspect of the curve monotonically decreases as the driving voltage increases in the range of about 1.6–3.0 volts, but at a driving voltage of about 3.2 volts, the intensities at a plurality of viewing angles begin to rise as the voltage increases from about 3.2 volts to 6.8 volts. This rise in intensity as the voltage increases is known as an "inversion hump." The inversion hump of FIG. 3 includes only a rise portion. However, such inversion humps often include both a rise and fall portion. The presence of this inversion hump with respect to a plurality of horizontal viewing angles as shown in FIG. 3 means that as gray level voltages between, for example, 1.6 and 3.0 volts increase, the intensity of radiation emitted from the pixel decreases accordingly. However, as gray level voltages above 3.0 volts increase from 3.2 volts all the way up to 6.8 volts, the intensity of radiation emitted from the pixel increases. This is undesirable. A perfect driving voltage versus intensity curve would have a decreased intensity for each increase in gray level driving voltage. In contrast to this, the inversion hump represents an increase in intensity of radiation emitted from the light valve pixel for each increase in gray level driving voltage above about 3.2 volts for certain viewing angles. Accordingly, it would satisfy a long felt need in the art if a liquid crystal display and pixels therein could be provided with no or little inversion. In other words, the smaller the rise in intensity for an increase in driving voltage at all gray levels, the better.

FIG. 4 is a schematic illustration showing an optical arrangement of a normally white liquid crystal display device disclosed in U.S. Pat. No. 5,184,236. As illustrated, the LCD includes a rear polarizer 111, a rear retardation plate or film 113, a liquid crystal cell 119 including a liquid crystal material sandwiched between a rear orientation or buffing zone oriented in direction A_0 and a front orientation or buffing zone oriented in direction A_1, a front retardation film 114, and finally a front polarizer 112.

The rear polarizer 111 is provided at the light incident side of the liquid crystal layer 119, a front or exit polarizer 112 is provided at the light exit side of the liquid crystal layer 119, a rear retardation film 113 is provided between the liquid crystal layer and the polarizer 111, and a front retardation film 114 is provided between the liquid crystal layer and the front polarizer 112. This prior art NW display is "P-buffed" because the rear polarizer transmission axis P_1 is parallel to the rear orientation direction A_0, and the front polarizer transmission axis P_2 is parallel to the front orientation direction A_1.